REPORT NO. CASD-NAS75-012
CONTRACT NAS8-31010

SPACE TUG AVIONICS DEFINITION STUDY

FINAL REPORT

VOLUME I • EXECUTIVE SUMMARY

GENERAL DYNAMICS
Convair Division

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VOLUME I ✦ EXECUTIVE SUMMARY

April 1975

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Prepared for
National Aeronautics and Space Administration
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FOREWORD

This final report on the Space Tug Avionics Definition Study was prepared by General Dynamics, Convair Division for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center in accordance with Contract NAS8-31010. The study was conducted under the direction of NASA Contracting Officer Representative, Mr. James I. Newcomb, and deputy COR., Mr. Maurice Singley.

The study results were developed during the period from July 1974 to March 1975. The final presentation was made at NASA/MSFC on 3 April 1975. Principal Convair contributors to the study were:

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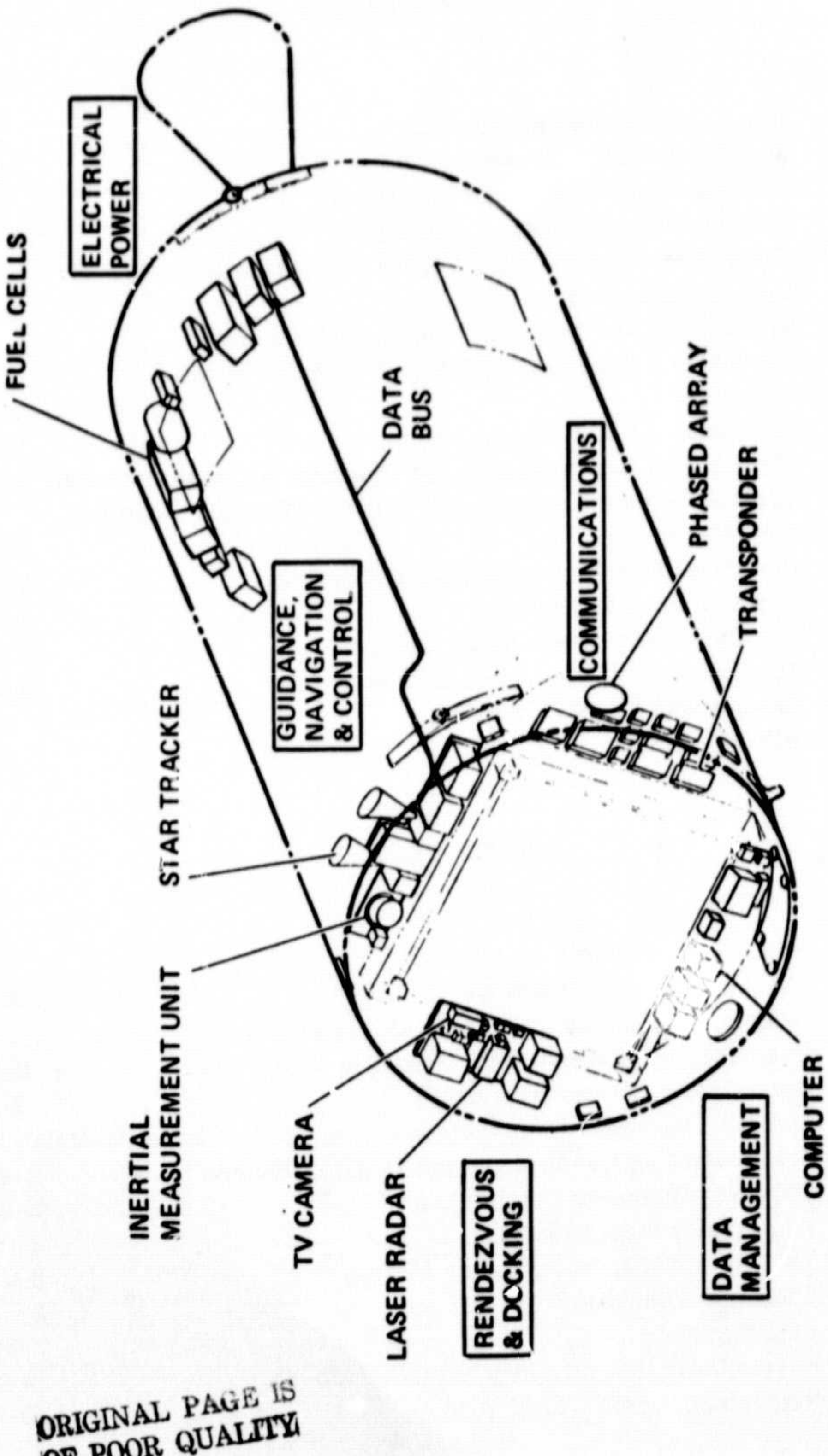
FUEL CELLS
ELECTRICAL POWER
DATA BUS
GUIDANCE, NAVIGATION & CONTROL
STAR TRACKER
INERTIAL MEASUREMENT UNIT
TV CAMERA
LASER RADAR
RENDEZVOUS & DOCKING
COMMUNICATIONS
PHASED ARRAY
TRANSPONDER
DATA MANAGEMENT
COMPUTER

SUMMARY

A goal of the Space Transportation System (STS) is to provide a broad range of accommodations to all payload users in a cost-effective manner. To do this, an upper stage is required to extend STS capability beyond the limits of the Orbiter. Current government plans call for the development by DOD of an interim upper stage (IUS), without payload retrieval capability, for use during 1980-1983, and development by NASA of the Space Tug for initial operations in 1983. The avionics system for the full-capability Space Tug will be driven by requirements to deliver, retrieve, and provide on-orbit servicing of payloads, and have a high degree of reuse. The 1978 Phase C/D timing will allow the Tug program to take maximum advantage of technology advances in the avionics implementation of these requirements. The definition of an avionics system for the Space Tug, utilizing 1978 technology concepts, was the objective of this study.

The significant achievements of the study are summarized below:

Requirements Established — The validity of the avionics system description is directly dependent upon realistic and complete definitions of avionics system requirements. A top down approach was used to identify, compile, and develop avionics functional requirements for all flight and ground operational phases. Such requirements as safety mission critical functions and criteria, minimum redundancy levels, software memory sizing, power for Tug and payload, data transfer between payload, Tug, Shuttle, and ground were established.

Those functional requirements that related to avionics support of a particular function were compiled together under that support function heading. This unique approach provided both organizational efficiency and traceability back to the applicable operational phase and event.

Each functional requirement was then allocated to the appropriate subsystems and its particular characteristics were quantified.

Volume II contains all of the avionics functional requirements.

Avionics System Defined — The architecture of the updated baseline avionics system is based on a modular computer concept incorporating dual redundant modules and multiple memory modules. The computer controls, sequences, and supports the other subsystems' computational requirements, which interface with the computer via a dual redundant digital data bus. Four major avionics subsystems interface via the data bus with this Data Management

Subsystem: Communications; Guidance, Navigation, and Control; Rendezvous and Docking; and Electrical Power. The system definition includes, in addition, the Tug to Shuttle/ground and Tug to payload interface implementations. Complete configuration definitions are contained in Volume III.

Subsystems Defined - Detailed definitions were developed for all of the avionics subsystem configurations. The five major subsystem configurations are summarized:

Data Management — Dual computer processor units (CPU's) are used in a self-test arrangement employing dual input/output processors (IOP's). Fault-tolerant memory modules are utilized with internal redundancy and error checking via a translator unit. The specific modular arrangement of hardware is adapted to the redundancy requirements of Tug using the Space Ultrareliable Modular Computer (SUMC) program. The CMOS/SOS technology is planned for implementing the computer for the achievement of sizeable power and weight savings.

Communications — The Airborne Electronically Steered Phased Array (AESPA) is baselined for long range transmission of data from the Tug. Omnidirectional antennas provide reception of commands and data and transmission in the vicinity of the Orbiter. The subsystem is dual redundant because of its safety-critical nature.

Guidance, Navigation, and Control — The IMU will achieve the equivalent of triple redundancy with only six laser gyros and six accelerometers in a dodecahedron configuration. Star and sun sensors are used for on-board attitude update. Interferometric landmark tracking (ILT) of ground based microwave radars enables autonomous updates of position and velocity.

Rendezvous and Docking — The Low Light Level Television (LLLTV) and the Scanning Laser Detection and Ranging (LADAR) sensor and their associated electronics are the main components of this subsystem. They represent a hybrid system that is primarily a manned remote rendezvous and docking capability with growth to an autonomous configuration.

Electrical Power — Primary dc power at a nominal 28 volts is supplied from dual lightweight, thermally integrated fuel cells that operate from propellant grade reactants out of the main tanks. An emergency battery provides additional safety protection.

Costs Estimated — A detailed estimate build-up approach was used to estimate EDD and total DDT&E costs. Costs were estimated at the component level (WBS level 7). The avionics system costs were developed for two conditions of technology accomplishments required for Tug. One condition represents accomplishing the technology work during the Tug development phase starting in late 1978, resulting in an avionics cost of \$94 million; the other condition represents those technology activities being accomplished during the period up to 1978, which are aimed at increasing confidence in techniques and concepts to be used and at reducing the concurrent development required of

a Phase C/D effort. The avionics cost uncertainty is reduced and estimated at $75 million.

SRT Efforts Defined — Specific supporting research and technology (SRT) activities have been identified that should be pursued to enhance the eventual Tug development effort. In addition, it is recommended that the Simulation/Demonstration program be pursued to assure a low risk development program by demonstrating selected techniques and simulating operations and configurations.

This study has shown that an advanced avionics system is necessary to support the reliability, long mission duration, and advanced functional requirements.

SECTION 1

INTRODUCTION

The avionics system for the full-capability Space Tug to be developed by NASA for initial operations in late 1983 will be driven by the requirements listed in Table 1-1. These requirements have a dramatic effect on the avionics needed for the Space Tug. Performance requirements to deploy 8000 pounds (3636 kg) of payload into or retrieve a 3500 pound (1590 kg) payload from geosynchronous orbit are supported by minimizing the avionics system weight. Safety and reliability requirements establish dual redundancy as the minimum level for all subsystems. Autonomy, and payload retrieval and servicing, are supported by new avionics sensors, techniques, and software. Mission durations in excess of 6-1/2 days have to have a compatible power system.

Table 1-1. Space Tug Demands on Avionics

DRIVING REQUIREMENTS		AVIONICS IMPACTS
PERFORMANCE	DEPLOY 8,000 LB RETRIEVE 3,500 LB	LOW SYSTEM WEIGHT
MISSION DURATION	6 1/2 DAYS	ELECTRICAL POWER CAPACITY
PAYLOAD RETRIEVAL & SERVICING	RENDEZVOUS & DOCKING	R&D SENSORS, CONTROL TECHNIQUES
AUTONOMY	MINIMUM GND SUPPORT	NAVIGATION UPDATE, CHECKOUT, REDUNDANCY MANAGEMENT
SAFETY & RELIABILITY	.97 MISSION SUCCESS	SUBSYSTEM REDUNDANCY — DUAL (MIN)
IOC 83	FIRST FLIGHT (1978 DEVELOP START)	IMPLEMENTATION USING 78 TECHNOLOGY

One of the most important factors is the 1983 schedule for the first operational flight. The 1978 Phase C/D timing will allow the Tug program to take maximum advantage of technology advances in the implementation of these avionics requirements with minimum risk and minimum DDT&F cost to attain power system capacity, adequate redundancy, new functions capability, and keep the total system weight at a minimum.

These are the driving functional requirements for which the Tug Avionics System was defined by this study.

1.1 STUDY OBJECTIVES

The primary objective of this study is to provide a detailed definition of the Space Tug Avionics System. The avionics system requirements are developed, compiled, and analyzed, and the configuration is baselined to the component level. Selected subsystems are analyzed and trade studies are conducted with special emphasis on the rendezvous and docking function. Redundancy management and Tug checkout activities are analyzed, and a commensurate data management subsystem is baselined. Avionics system/Orbiter and Tug payload interface requirements are defined, and specific supporting research and technology programs are recommended.

1.2 TECHNICAL APPROACH

This study consisted of engineering and planning analyses conducted over a period of eight months. The technical approach centered upon updating the MSFC-supplied avionics system definition contained within the Space Tug baseline documents (MSFC 68M00039-1, Requirements and Guidelines; 68M00039-2, Configuration Definitions; 68M00039-3, Flight Operations; 68M00039-4, Ground Operations, Verification, Analysis, and Processing).

The elements of that update were:

a. Establishment of avionics functional requirements as derived from flight and ground mission phases.

b. Substantiation of configuration selections with trade studies and analyses.

c. Definitions of subsystems to the component level.

d. Integration of the subsystems into a functionally compatible avionics system.

e. Development of interface requirements and interface implementation.

Special emphasis tasks covering rendezvous and docking, redundancy and data management system, and checkout were conducted in parallel to provide a detailed definition of these areas. A unique feature of our approach included a simulation of the remote manned rendezvous and docking function to evaluate this method as a viable option to the completely autonomous methods. Convair has an ongoing IRAD in this area and a visual display laboratory. The availability of this facility and simulation allowed a definitive study of the remote manned rendezvous and docking within the available resources. The results of the special emphasis tasks, along with the trades, are incorporated into the final baseline avionics system definition. In addition, analyses were conducted to define a simulation and demonstration plan and required SRT.

1.3 RELATIONSHIP TO OTHER NASA EFFORTS

Four companion Tug-related studies were conducted by MSFC in parallel with this study. They were:

OOS/Tug Payload Requirements Compatibility Study

OOS/Tug Orbital Operations and Mission Support Study

Space Tug/Shuttle Interface Compatibility Study

Tug Fleet & Ground Operations Schedule & Control Study

Functional requirements and other pertinent technical data were exchanged at regular interval meetings to maximize the benefit of data generated among all of the studies.

SECTION 2

SIGNIFICANT ACHIEVEMENTS AND ACTIVITIES

The definition of the baseline avionics system for the Space Tug was the primary accomplishment resulting from all of the analyses of this study. The elements of that definition include: 1) the avionics functional requirements, 2) the system configuration and interfaces with the Shuttle and the Tug's payload, 3) the avionics subsystems/component descriptions, and 4) the costs, and development and simulation/demonstration plans. This section presents a summary of those four elements of the baseline avionics system definition including a summary of the results from some of the significant trade studies; particularly, the demonstration of a remote manned rendezvous and docking system using Convair's Visual Display Simulator.

Six major study tasks, all running concurrently, provided the organization for the analysis activities within this study. They were:

- Task A - Avionics System Baseline & Interface Requirements Definition
- Task B - Baseline of Rendezvous & Docking System Hardware
- Task C - Redundancy Management, Data Management Subsystem Definition and Software Analysis
- Task D - Tug Checkout Requirements and Methodology Analysis
- Task E - Simulation/Demonstration Test Program
- Programmatics - Cost Analyses

Tasks A, B, C, and D encompassed all of the requirements development, and the configuration and option selection trades that generated the information necessary for system, subsystem, and component definitions. Programmatic analyses developed the costing methodology and cost estimates. Task E established the comprehensive planning for avionics system development including early program activities to simulate and demonstrate those advanced concepts incorporated in the system definition that would assure a low risk development program at Phase C/D.

2.1 AVIONICS FUNCTIONAL REQUIREMENTS

The avionics requirements that have been developed in this study, as well as those identified in the MSFC Space Tug baseline documents, have been compiled into an Avionics Functional Requirements Document (Volume II of this final report). The avionics functional requirements have their source in the events occurring within each flight (mission) and ground operational phase. Analysis of each event identified the kind of support required from the avionics system. Out of the nine operational phases,

covering all ground turnaround events and flight events, 10 different kinds of avionics support functions were identified as shown in Table 2-1. The detailed avionics functional requirements were compiled and grouped according to their associated support function. For example the requirements associated with the safety and reliability support functions are shown in Table 2-2. Each functional requirement is allocated to one or more of the avionics subsystems, and the quantification of each functional requirement is identified according to the particular characteristics of each applicable subsystem. There are 13 similar tables in Volume II of functional requirements listed by support function. The advantages of this organizational approach for functional requirements are: 1) the grouping of associated requirements by function, 2) the allocation to subsystems, 3) traceability to the operational phases and events, and 4) compilation of the functional requirements as they apply to each subsystem with subsequent allocation and quantification to the elements and components of that subsystem.

2.2 AVIONICS BASELINE SYSTEM DESCRIPTION

The baseline Space Tug Avionics System is shown in Figure 2-1. Its configuration features six major subsystems integrated into an advanced avionics system through a digital data bus technique under the control of a modular central computer. The dual data bus is depicted by the broad dark and light arrows connecting the remotely located digital interface units (DIU) with the computer through a computer interface unit (CIU). Those are the major components of the Data Management Subsystem, which interfaces with and controls all of the functional elements on the Space Tug. The other five avionics subsystems are (from left to right) the Communications Subsystem, highlighted by the three electronically steerable phased arrays; the Rendezvous and Docking Subsystem, with the scanning laser radar (LADAR) and TV; the Guidance, Navigation, and Control Subsystem incorporating a dodecahedron laser gyro inertial measurement unit (IMU); one of three signal conditioners and sensors of the instrumentation subsystem; and, below, the Electrical Power System using dual fuel cells and power processing units (PPU) and two power distribution units (PDU), one aft and one forward. The figure attempts to portray some physical relationship of the locations of the avionics components to the Space Tug vehicle and to the level of redundancy incorporated into the system. The aft DIU interfaces to most of the non-avionics systems for which control by the central computer is necessary. These involve valve controls for venting, fluid fill and drain, and main engine ignition and shutdown, as well as on-off control for helium pressurization and propellant mixers in the main tanks.

The other two primary interfaces are with the Shuttle and ground, and the Tug's payload. The bottom of the diagram shows the functions associated with the Tug to Shuttle interface via the deployment adapter. For example, the safety monitors are hardwire connections directly from the instrumentation sensors to the Orbiter's caution and warning system. The same safety data (from redundant instrumentation sensors) is redundantly supplied to the Orbiter and/or ground system via the telemetry downlink out of the CIU, once the data has been processed through the appropriate signal conditioner, DIU and data bus.

Table 2-1 Avionics Support Functions

MISSION PHASE	AVIONICS SUPPORT FUNCTIONS PER MISSION PHASE
5. POST LANDING OPERATIONS	• Safety • Checkout: Status Check • Interfaces: Tug/Ground; Tug Spacecraft; Tug/Shuttle
4. REFURBISH & CHECKOUT	• Safety • Checkout: Calibration, Initialization Functional Test • Interface: Tug/Ground
3. TUG/SPACECRAFT MATE AND CHECKOUT	• Safety • Checkout: Status Checks • RF Communication • Interfaces: Tug/Spacecraft, Tug/Ground • Operations Control & Sequencing
2. TUG/SPACECRAFT/ORBITER MATE & CHECKOUT	• Safety • Checkout: Status Check • Operations Control & Sequencing • Interfaces: Tug/Shuttle; Tug/Ground
1. LAUNCH OPERATIONS	• Safety • Checkout: Status Check • Operations Control & Sequencing • Interfaces: Tug/Shuttle; Tug/Ground
14. ASCENT FLIGHT	• Safety • Checkout: Status Check; Calibration; Initialization • Operations Control & Sequencing • RF Communications • Attitude Control • Electrical Power • Interfaces: Tug/Shuttle; Tug/Spacecraft
13. ABORT	• Safety • Checkout: Status Check • Operations Control & Sequencing • Attitude Control • RF Communications • Interface: Tug/Shuttle; Tug/Spacecraft
15. TUG FLIGHT OPERATIONS	• Trajectory Control: Navigation; Guidance; Flight Control • Attitude Control: Coast; Maneuvering • Operations Control & Sequencing • RF Communications • Rendezvous & Docking • Safety • Checkout: Status Check; Maintenance Support • Interface: Tug/Spacecraft • Electrical Power • Reliability
12. TUG RETRIEVAL, ENTRY, LANDING	• Safety • Checkout: Status Check • Attitude Control • Operations Control & Sequencing • RF Communications • Interface: Tug/Spacecraft; Tug Shuttle

AVIONICS SUPPORT FUNCTIONS

- SAFETY
- RELIABILITY
- OPERATIONS CONTROL & SEQUENCING
- RF COMMUNICATIONS
- RENDEZVOUS & DOCKING
- CHECKOUT
- INTERFACES
- ELECTRICAL POWER
- TRAJECTORY CONTROL
- ATTITUDE CONTROL

Table 2-2. Avionics Safety and Reliability Requirements

SUPPORT FUNCTION	FUNCTIONAL REQUIREMENTS	ALLOCATION TO SUBSYSTEMS & QUANTIFICATION OF REQUIREMENTS					
		DATA MGMT.	ELECT. POWER	GUID, NAV & CONT	REND & DOCK	COMMUN.	INSTRUM.
SAFETY	No single failure shall result in a hazard which jeopardizes flight or ground crews, public or private property or ecology.	Dual capability required	Dual power sources and dual distribution systems	Dual capability for attitude control & inertial reference during deploy/retrieval of Tug by Orbiter.	Passivate system while Tug is in or near Orbiter	Dual capability required for transmission of status data.	Dual transducers/ signal conditioners
	As a minimum, Tug will be able to sustain a failure and retain the capability to successfully terminate the function without injuring personnel, damaging facilities or jeopardizing Orbiter or payload.	Either triple DMS with voting logic or dual DMS with self check capability.	Failure detection & switchover.	Failure detection & switch-over capability	Crew controlled interlock.	Failure detection & switchover.	Failure detection & switchover.
	During all ground operations and all flight operations of launch, deploy, retrieve and entry, Tug will provide data to the Orbiter on Tug/spacecraft status and condition. Provision will be made for Orbiter crew override of safety critical functions.	Crew controlled interlocks to prevent inadvertent operation of: • Main engine • Aux. Prop. Sys. • Mechanisms	C&W parameters • Fuel cell temp • Bus voltage	Status data on attitude control & inertial ref. systems during Tug deploy/ retrieve.	Crew controlled interlock	Provide RF link when Tug is outside of Orbiter. Provide hardwire link when Tug is inside Orbiter.	C&W parameters: • H_2 tank pressure • O_2 tank pressure • N_2H_4 tank temp. • H_e pressure • Orbiter attach • Spacecraft attach • Arm safe main engine • Arm safe ACS • Umbilical monitor • Fuel cell LH_2 tank pressure • Fuel cell LO_2 tank pressure

SUPPORT FUNCTION	FUNCTIONAL REQUIREMENT	ALLOCATION TO SUBSYSTEMS					
		DATA MGMT.	ELECT. POWER	GUID, NAV & CONT.	REND & DOCK	COMMUN.	INSTRUM.
RELIABILITY	Avionics System Reliability = 0.992. (This is avionics system apportionment to realize mission reliability of 0.97 - liftoff through landing.)	.99869	.99945	99682	.99985	.99923	.99794

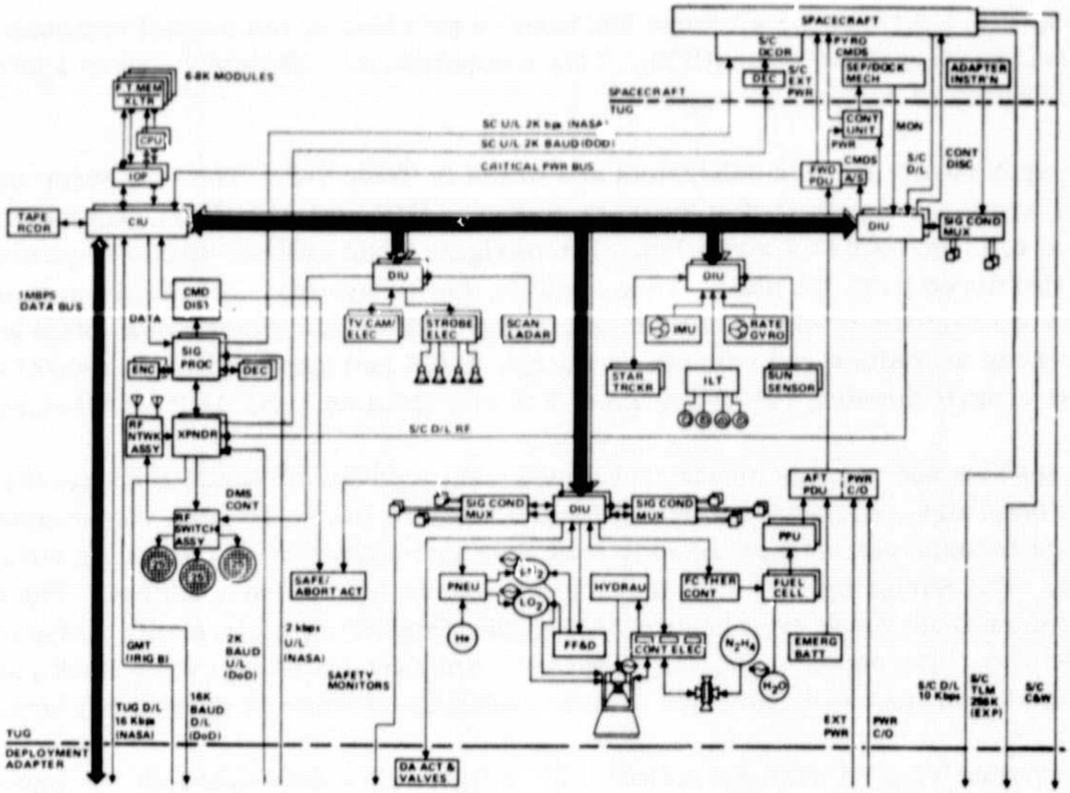

Figure 2-1. Tug Avionics System Baseline

The Tug to payload interface is shown in the upper right corner of the figure. A forward DIU accommodates the primary control to and data input from the payload. Power is supplied to the payload from the Tug whether it be from the Tug's fuel cells or from some external power source.

The avionics system incorporates advanced technology concepts and components. All of these technologies are in development at this time. No new technologies requiring advanced breakthroughs were identified. The system was baselined for autonomous operations but with backup ground support. Total system weight is 898 lb (408 kg).

2.3 AVIONICS SUBSYSTEM DESCRIPTIONS

The major subsystem configuration descriptions are presented in this section. Included are some of the driving requirements, trade studies results, and summary conclusions.

2.3.1 <u>GUIDANCE, NAVIGATION, AND CONTROL SUBSYSTEM.</u> This subsystem provides all of the sensor information necessary to determine the state of the vehicle's position, velocity, and attitude, and to autonomously perform an update to that information from independent references such as, the stars, sun and known landmarks. Included in this subsystem are the electronics associated with processing thrust vector control actuator signals as well as attitude control signals to the reaction jets. The

computational support for all these functions is provided by the central computer in the Data Management Subsystem (DMS). This computational software requires approximately 11,300 words of memory storage.

The requirements for this subsystem are listed in Table 2-3. The IMU error source values are those expected of an average accuracy IMU, the significant value being gyro drift at 0.1 deg/hour (1.7 mrad/hr). The navigation and attitude update requirements were developed from the major trade study in this subsystem. A subsystem meeting these requirements would be capable of placing payload into synchronous orbit with an uncertainty in position and velocity of 8 n.mi. (14.6 km) and 8 ft/sec (2.4 m/s) meeting the overall injection requirements of 9 n.mi. (16.4 km) and 11 ft/sec (3.4 m/s).

Four position and velocity update techniques were evaluated: Horizon Scanners, Navigation Satellites, Interferometric Landmark Tracker (ILT), and one-way Doppler. The Horizon Scanner system was the only technique that did not meet the update requirements. The Navigation Satellite technique is usable only at low altitudes. The ILT was the preferred approach even though the one-way Doppler was acceptable (being developed for Shuttle). The one-way Doppler requires a very accurate and stable clock possibly with an atomic frequency standard with an attendant increase in operational complexity.

Four candidate IMU's were evaluated: Laser Gyros (in a dodecahedron configuration), Electrostatically Suspended Gyros (in the MICRON system), a conventional Strapdown System (DIGS), and a gimbaled platform system (KT-70). The latter two were included as representative systems in their class of IMU's. All units meet the basic performance requirements, with little benefit to be gained from increased performance because of the necessity of updating to support even the shortest mission. Therefore, the IMU

Table 2-3. Guidance, Navigation, and Control Requirements

- IMU REQUIREMENTS

	1σ VALUE
MISALIGNMENT	72 ARC SEC
ACCEL BIAS	100μG
ACCEL SF	60 PPM
GYRO FIXED DRIFT	0.1 DEG/HR
GYRO SCALE FACTOR	55 PPM

- NAVIGATION UPDATE ACCURACY/UPDATE TIME REQUIREMENT

1σ ACCURACY	~4 FPS, 1.5 NM
UPDATE	~3 HOURS BEFORE APOGEE BURN FOR MIDCOURSE CORRECTION

- ATTITUDE UPDATE ACCURACY REQUIREMENT

1σ ACCURACY	~0.04 DEG
UPDATE	~15 MIN BEFORE ENGINE BURNS

YIELDS 8 NM, 8 FPS

GEOSYNCH - PAYLOAD INJECTION ACCURACY REQUIREMENT: 9 NM, 11 FPS

requirements were relieved and the error contributions to the position/velocity uncertainty balanced between the IMU and the update system. However, the MICRON system does not support the reliability requirement (even in a triple redundant configuration); it has a low shock tolerance, and its superior gyro drift is of little value for the Tug mission. The strapdown (dual redundant) and the gimbaled (triple redundant) systems are both heavy and expensive. The laser gyro offers superior reliability, having no moving parts, and in a dodecahedron configuration provides the necessary inertial information after two failures. It has the lowest unit cost and represents the least operationally complex IMU. The GN&C baseline subsystem is shown in Figure 2-2. A major element of this subsystem is the computational software required to process the sensor information including fault detection and isolation, perform coordinate transformations, determine navigational states, and compute and issue guidance commands as well as stability and control commands. Approximately 11,300 words of central computer memory have been estimated for this computation effort.

The attitude update sensors are the Startrackers and sun sensors (both dual redundant). A dodecahedron laser rate gyro unit has been baselined to provide redundant rate input to the stability and control function. Once Tug bending modes are determined (Phase C/D), derived rate may be the preferred approach, thereby deleting the need for a rate gyro package.

The advanced technologies associated with the laser gyro, dodecahedron fault detection and reconfiguration, and the ILT are all in development with current on-going contractual programs. No unique breakthrough requirements were identified in support of the full-capability Tug development program.

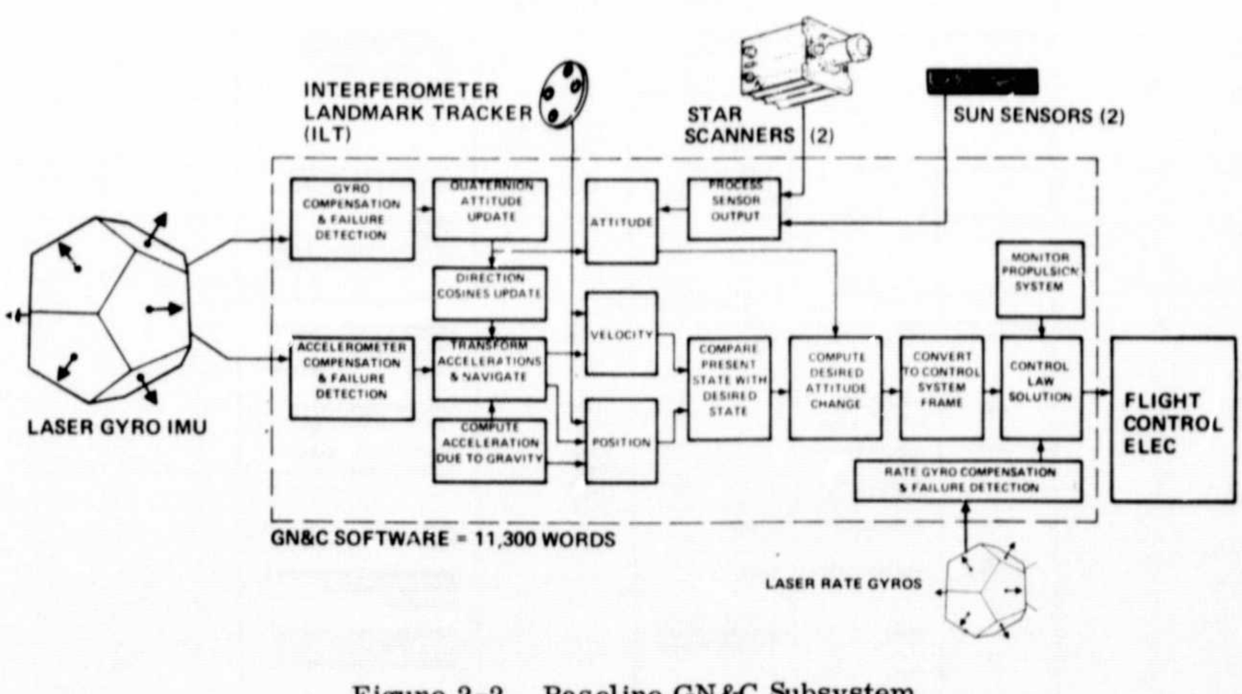

Figure 2-2. Baseline GN&C Subsystem

2.3.2 COMMUNICATIONS SUBSYSTEM.

RF communications between the Tug, the Shuttle, and the ground (including via a tracking and data relay satellite, TDRS) is the primary function of the communications subsystem. It contains those components necessary to transmit and receive clear or secure communications on S-band, decode and distribute received commands, relay command messages to the payload, and interleave payload data with that of the Tug for transmission to appropriate operations receivers.

Table 2-4 summarizes the driving requirements for the communications subsystem. Foremost is the requirement for compatible operations with the NASA and DOD communications networks (STDN and AFSCF) and with the TDRS. Different frequencies and modulation techniques require a versatile signal processing capability. Common antennas can be used across the frequency range from 1750 MHz to 2300 MHz, but module and mode switching is necessary to properly modulate/demodulate the signals. TDRS is the driver on link parameter requirements. The effective isotropic radiated power (EIRP) from Tug when communicating with TDRS is 23 dBW (160 watts with 0 dB omni antenna) appropriately implemented with a directive antenna. In the vicinity of the Shuttle, the EIRP requirement is 3 dBW, implemented with an omni antenna and an input power to the antenna of four watts. The table includes the performance capability

Table 2-4. Communications Requirements

PARAMETER	DRIVER	REQUIREMENT: FORWARD LINK	REQUIREMENT: RETURN LINK	PERFORMANCE BASELINE CONFIGURATION
NETWORK COMPATIBILITY & OPERATIONS				
RF	STDN	2025 - 2100 MHz	2200 - 2290 MHz	
	TDRS	2028.1354 – 2115.6154 MHz	2202.500 – 2297.500 MHz	
	AFSCF	1763.721 – 1839.795 MHz	2202.510 – 2297.510 MHz	
MODULATION	STDN	AM/PSK/PM 70 KHz SCO		STDN, TDRS, OR AFSCF NETWORKS SELECTED BY MODULE & MODE SWITCHING
	TDRS	TDM/PSK SPREAD SPECTRUM	PCM/PSK DIRECT	
	AFSCF	AM/FSK/PM	PCM/PSK/PM 1.024 MHz SCO	
SECURITY	DOD	COMMAND DECRYPTION	DATA ENCRYPTION	GFE SECURITY DEVICES WITH BYPASS CONTROL
REDUNDANCY	SAFETY	DUAL	DUAL	MULTIPLE ELEMENT PHASED-ARRAY ANTENNA, DUAL ELECTRONICS WITH FUNCTIONAL CROSS-STRAP
LINK REQUIREMENTS				
$EIRP_{max}$	TDRS		23 dBW	PHASED ARRAY ANTENNA $EIRP_{BORESIGHT}$ 28 DBW $EIRP_{60°}$ 23 DBW
$EIRP_{min}$	TUG/ORBITER LINK TO 20 NMI		3 dBW	OMNI ANTENNA SYSTEM 4 WATT TRANSMITTER
BIT RATES	TUG ENGR DATA SC DATA ENCODED DATA HIGH RATE DATA		16 kbps 10 kbps 64 kbps 256 kbps	SELECTABLE BIT RATES 16, 64 & 256 kbps
	COMMAND DATA	2 kbps		NASA 2 KBPS DOD 2K BAUD
COVERAGE	ORBITER SAFETY	OMNI		OMNI RECEIVE; SELECTABLE OMNI OR DIRECTIVE TRANSMIT
LINK MARGIN	TDRS	FORWARD ERROR CONTROL CODING		CONVOLUTIONAL ENCODE AND DECODE RATE 1/2 CONSTRAINT LENGTH 7

of the selected baseline subsystem. The directive antenna is an electronically steerable phased array. This study determined that an array with 25 active 1 watt elements would provide adequate gain to meet the EIRP requirements. The 20 degree (0.35 radian) wide beam is steerable to ±60 degrees (1.05 radians) from the array boresight. The number of arrays required to provide nearly all attitude communications was determined to be three, spaced 120 degrees (2.1 radians) around the circumference of the forward end of the shell. Three arrays provide the most effective coverage. Four arrays increase the coverage only 7% at the expense of an additional array and the attendant system complexity.

The critical functions, with the potential of creating a safety hazard for the Shuttle and crew, are monitored whenever the Tug is in or near the Shuttle. RF communications is a vital link in providing this data to the Orbiter for display and/or caution and warning and dictates a minimum of dual redundancy in the communication subsystem. The communications baseline subsystem is shown in Figure 2-3. The significant system feature is the transmit-only mode required of the phased arrays. Uplink signals are exclusively received using the omnidirectional antennas. This eliminates the need for antenna selection and beam steering to receive commands. The antenna selection and beam steering depend upon the vehicle attitude (knowledge stored in the Data Management Subsystem, DMS). Control for both functions comes from the DMS. The electronics are dual redundant with cross-strapping. Provisions for encryption and decryption devices are available with bypass capability when not needed.

The phased array technology is also in development. With the requirement to transmit only, the element module design should be simpler, not requiring a diplexer or receive amplifier. The transponder and signal processor utilize current LSI technology.

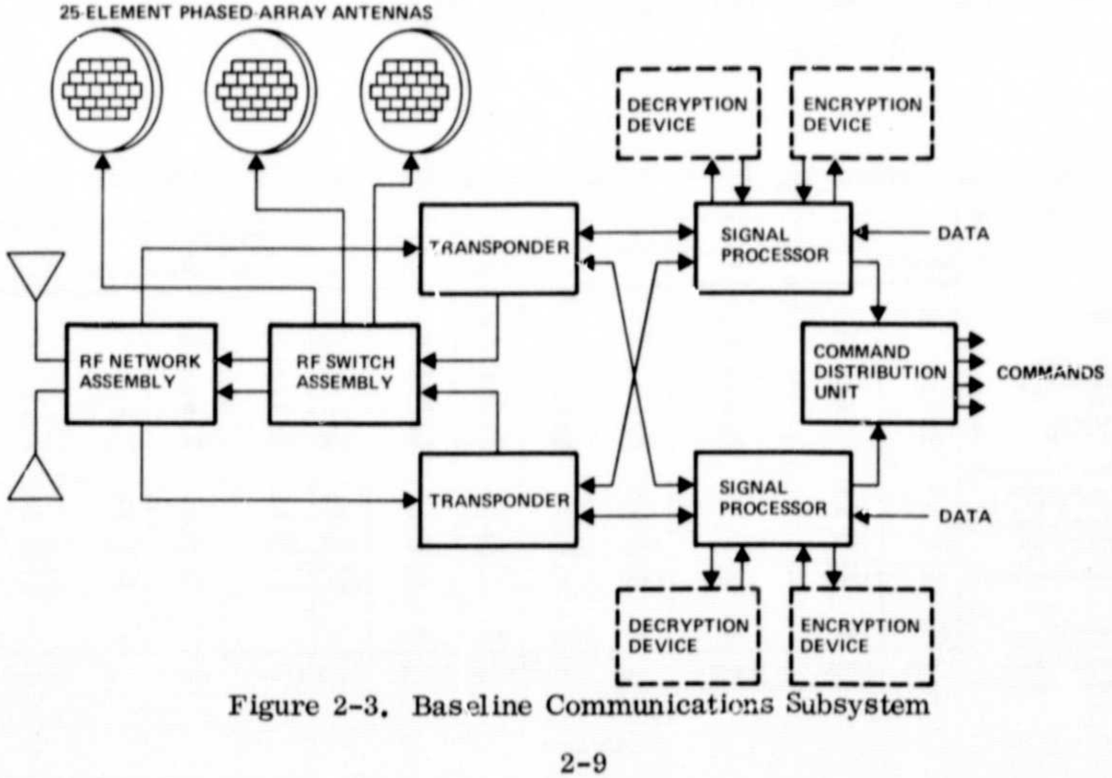

Figure 2-3. Baseline Communications Subsystem

2.3.3 ELECTRICAL POWER AND DISTRIBUTION SUBSYSTEM. Supplying electrical power in support of the Tug systems and its payload for missions of six days duration dictates the use of fuel cells as the primary power source. The power requirements drive the fuel cell power output capability, and the safety requirements drive the need for dual redundant independent power systems and an emergency battery to assure power to critical subsystems and instrumentation sensors. Power requirements account for the total Tug power needs (avionics and non-avionic systems, heaters, etc.) and support for the payload power requirements – all of which vary with each phase of the mission. These requirements have been compiled by mission phase as shown in Table 2-5. Based on these requirements, each fuel cell was sized for an average output of 2000 watts.

Two fuel cell technologies are currently under development. Both of these were evaluated for application to the Tug. One is an adaptation (resized) of the high pressure fuel cell being developed for the Shuttle. This fuel cell requires supercritical storage for the hydrogen and oxygen fuel cell reactants. The other is a new technology that is greatly reduced in weight and operates with reactants at low pressure. This lightweight fuel cell could use reactants from the main propellant tanks. Figure 2-4 shows the two technology-option power plants and the peripheral equipment necessary to the definition of a complete power system. The peripheral equipment common to both are the electrical and temperature control emergency battery, purge controls, circulating pumps, and space radiators for waste heat rejection. The significant difference between them is the supercritical storage system which requires separate tanks and fill and drain equipment, and which accounts for 125 lb (56.8 kg) of the 374 lb (170.0 kg) weight difference. The power plants account for 212 lb (96.4 kg) of the difference. Included in the integrated lightweight fuel cell system is a heat exchanger which uses all or part (depending on electrical load) of the waste heat from the fuel cell to warm the hydrazine propellant of the APS system.

Table 2-5. Typical Tug Power Requirements Per Flight Phase (Watts)

	ASCENT	PREDEPLOY C/O	DEPLOY TUG	ON-ORBIT PL C/O	COAST	ENG BURN	GUID UPDATE	R&D	RETRIEVAL NORMAL	RETRIEVAL EMERG	DESCENT	RTLS ABORT
AVIONICS												
DATA MGT	99	114	114	114	114	134	134	134	114	114	99	114
GN&C	–	382	382	382	382	382	382	382	382	340	–	–
R&D	–	50	–	–	–	–	–	50	–	–	–	–
COMMUNICATIONS	10	10	72	72	95	165	165	165	72	72	10	10
INSTRUMENTATION	66	66	66	66	66	66	66	66	66	66	66	66
POWER SYS	115	140	130	130	130	140	130	140	130	49	115	115
AVG HEATERS	30	230	37	14	21	17	9	41	14	7	4	30
AVIONICS TOTAL	320	992	801	778	808	904	886	978	778	648	294	335
OTHER TUG REQUIREMENTS												
MAIN ENG CIR PUMPS	–	40	40	40	40	–	40	40	40	5	40	40
CONTROL V's & "O" g VENT	225	256	281	225	201	536	218	261	281	174	364	728
APS MOTOR HEATERS	–	–	–	–	64	50	30	50	50	20	–	–
OTHER SYS TOTALS	(225)	(296)	(321)	(265)	(305)	(586)	(288)	(351)	(371)	(199)	(404)	(768)
TOTAL TUG REQUIREMENTS	545	1,288	1,122	1,043	1,113	1,490	1,174	1,329	1,149	847	698	1,103
SINGLE PL REQUIREMENTS	600	650	700	700	200	200	200	–	–	–	40	–
TUG POWER REQUIREMENT	1,145	1,938	1,822	1,743	1,313	1,690	1,374	1,329	1,149	847	738	1,103

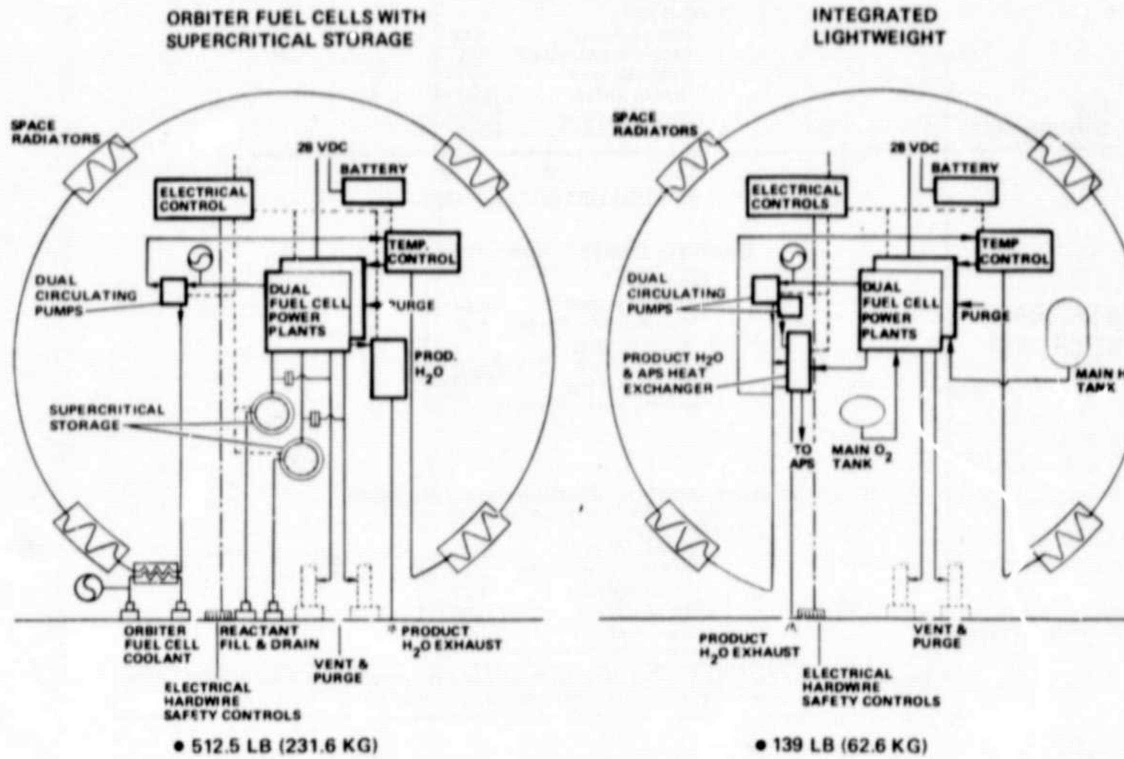

Figure 2-4. Electrical Power Source Options

The lightweight fuel cell technology was selected as the baseline power plant because it is the only option that meets the power system weight limit that is associated with the Tug performance baseline of placing 8000 lb (3636 kg) of payload into geosynchronous orbit as shown in Figure 2-5. The figure relates power system development cost and payload penalty or gain to each fuel cell type. The modified Orbiter with high pressure supercritical reactant storage is at bottom of chart and the lightweight system at the top above the Tug performance baseline criteria. Payload gain or penalty associated with three types of missions is shown including the payload-to-Tug dry-weight sensitivity factor for each mission. An additional option is shown, an adaptation of the Orbiter technology fuel cell to operate with reactants from the main propulsion tanks (low pressure). All three power systems are estimated to have a development cost of approximately $13 million. The relative costs between fuel cell power plants, peripheral equipment, and integrated systems testing are indicated by the lengths of the bar segments.

The power processing and distribution components of the power distribution system can be seen in the avionics system diagram, Figure 2-1. Remote power controllers (solid state) within the power distribution units (PDU) control the application of power to each of the hardware components via commands through the data bus and DIU's. Here again, the technologies are advanced but in work.

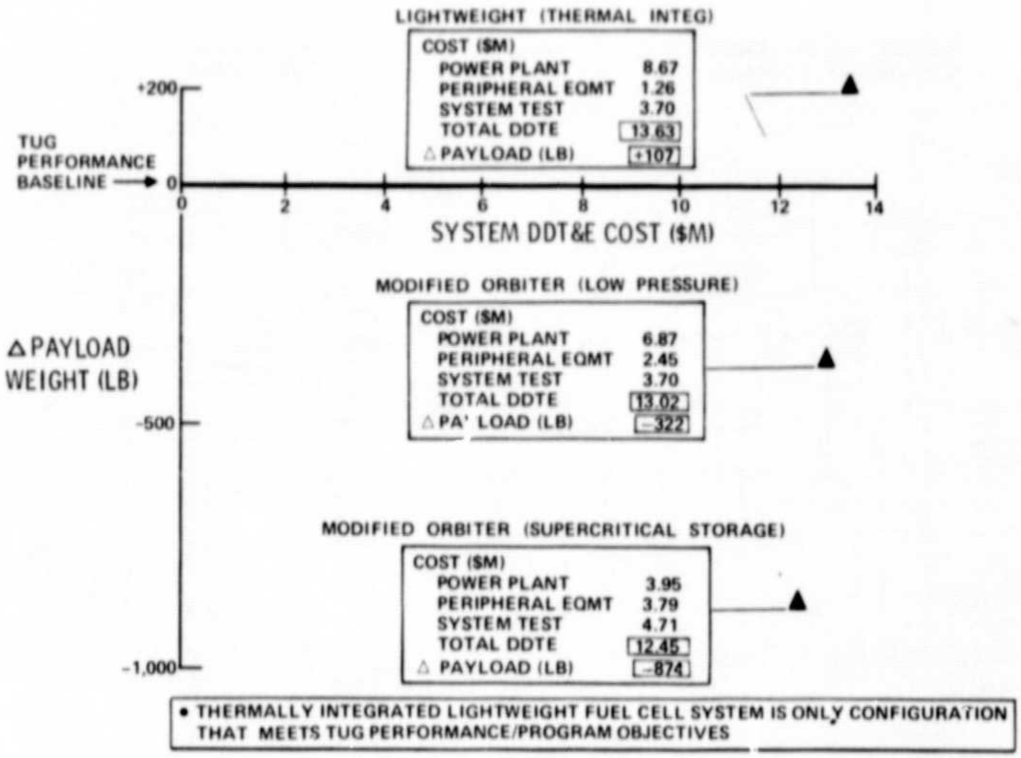

Figure 2-5. Power System Capability Impact Versus Relative Development Cost

2.3.4 <u>RENDEZVOUS AND DOCKING SUBSYSTEM.</u> Payload rendezvous and docking represents the major capability difference between an interim and the full-capability Tug. Tug mission requirements include rendezvous and docking functions for payload retrieval and potentially for payload servicing.

The rendezvous and docking functions consist of six elements or phases as shown in Figure 2-6. Payload acquisition, tracking, and ranging are associated with rendezvous; payload inspection (stationkeeping), docking port alignment, closing, and capture are all part of the docking function.

Rendezvous and docking subsystem performance was evaluated on one autonomous candidate and one remotely manned candidate. The main hardware component of the autonomous subsystem is a scanning Laser Detection and Ranging (LADAR). Software for processing the sensor input data by estimating the payload relative state vector and computing the thrust program according to a control algorithm (see Figure 2-7) is the other important element. The control loop, from LADAR sensor to thrust commands, is onboard the Tug and does not require support outside of the Tug. A large part of the software in support of rendezvous and docking is actually that employed in processing navigational functions. Docking capability is provided through the discrimination among four retroreflectors in a skewed-T configuration.

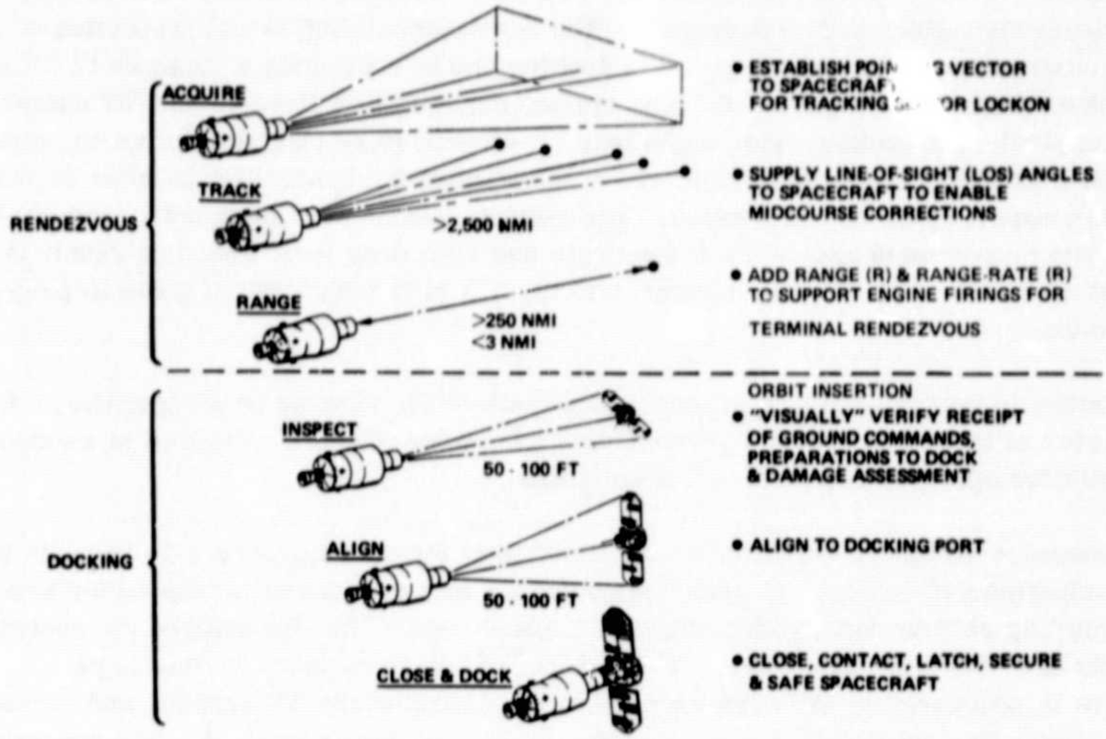

Figure 2-6. Rendezvous and Docking Functional Elements

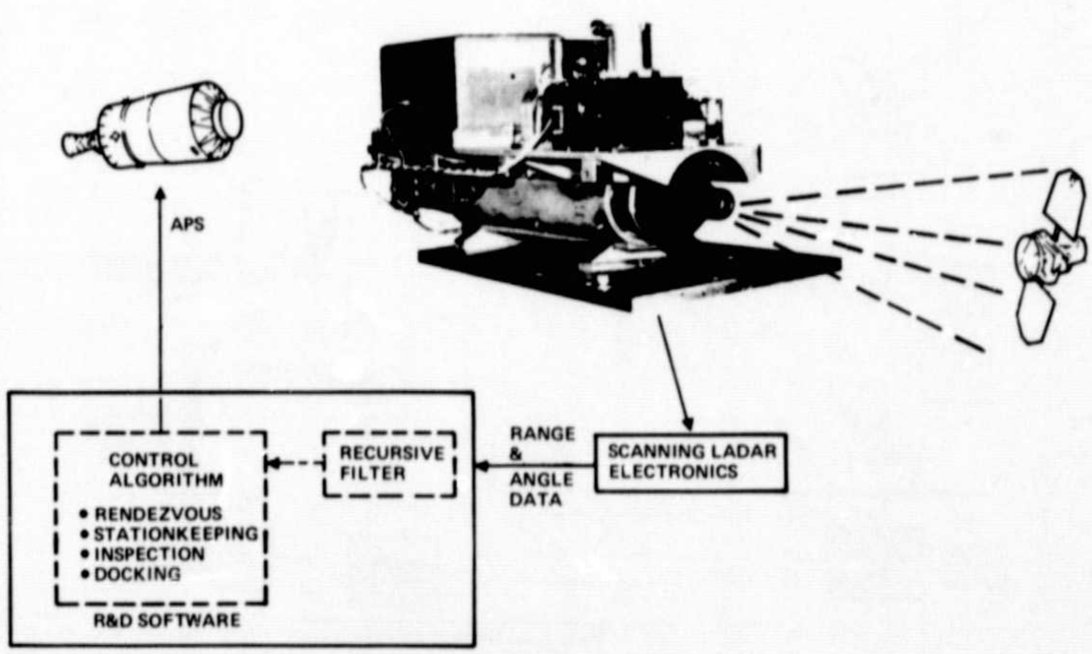

Figure 2-7. Rendezvous and Docking Subsystem Autonomous Candidate

The LLLTV sensor system performs two primary functions: manned, remote docking, and visual inspection of the spacecraft. The requirements for visual inspection of the spacecraft after deployment or prior to docking can be met using a "snapshot" TV approach as depicted in Figure 2-8. The system consists of a fixed-mount TV camera with an electronic shutter, wide angle lens (30-degree (0.52 rad) field of view), and a silicon intensified target (SIT) vidicon. A snapshot of the spacecraft is taken by momentary exposure of the SIT vidicon. The vidicon retains the image until read out by a scanning electron beam. A slow scan rate and 4 bit gray level encoding result in a digital data rate of 50 Kbps as compared to the 2.5 MHz bandwidth of general-purpose television.

The image is transmitted to a ground-based console for viewing by an operator. A scan converter at the ground station reconstructs the image where it is stored in a video disc file for operator retrieval and examination.

The snapshot system of providing a single image to the operator every 16 seconds for his evaluation and control has been demonstrated as a successful technique for accomplishing Tug rendezvous and docking with a spacecraft. The elements of the operator's console are shown in Figure 2-9. The spacecraft image as taken by the Tug's TV camera is processed by the scan converter, displayed on the TV screen, and stored in the video disc recorder or video tape for future operator retrieval. The operator's console contains the controls for positioning, sizing, and orienting a reticle by which range and attitude correction commands are generated. The ground-based computer processes the Tug's state vector information with the operator's reticle adjustments and provides the range and angle correction data to the Tug's flight computer for

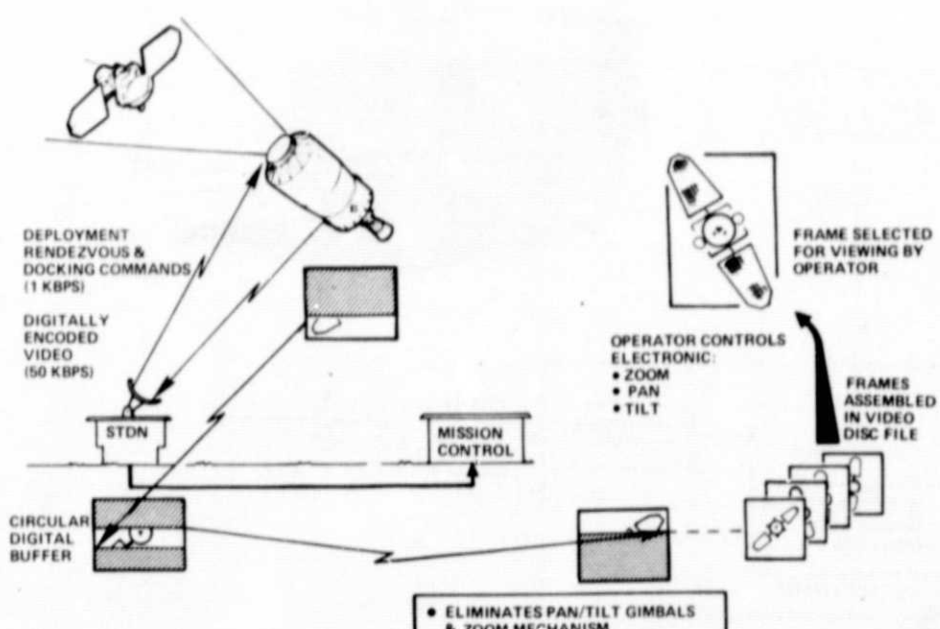

Figure 2-8. Slow-scan LLLTV Operation

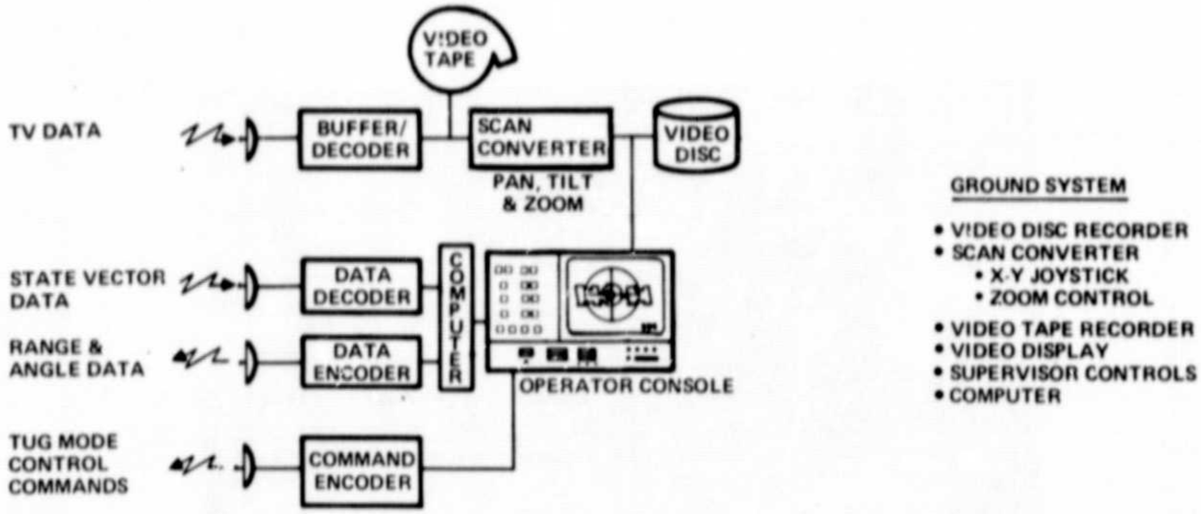

Figure 2-9. Elements of the Ground-based Operator's Console System

execution. Tug mode controls provide on-off discretes and override commands. The data being transferred to and from the Tug are separated for clarity.

The docking strategy for the remote-manned subsystem is to place the remote operator in a supervisor's role rather than a controller's role. This means that he can operate at a much reduced task load, delegating much of the operation to the spaceborne and ground computers. In essence, Tug provides task continuity and the basic docking operation, whereas the supervisor operates as a feedback sensor (via positioning the reticle) removing accumulated biases, and accomplishes overall operation evaluation/decision making.

The supervisor's console for Convair's Manned-Remote Rendezvous and Docking Simulation study is representative of what would be required at a ground installation (Figure 2-10). In addition to the digital displays — to the left of the TV monitor — are status, caution, and warning lights on the facade below the monitor. Controls for placing, sizing, and orienting the range reticle — shown on the screen — are contained on the central console panel. It is the reticle that provides the principal feedback from the ground-based supervisor.

In this sense, the supervisor is not a controller or pilot but is providing feedback for the proper sensor input to the control algorithm onboard the Tug. The panel immediately to the right of the reticle controls, commands the flight mode and closure velocity. On the far right are the video disc controls. On the far left are spacecraft controls that are operative if the spacecraft were to be an active element in the docking process.

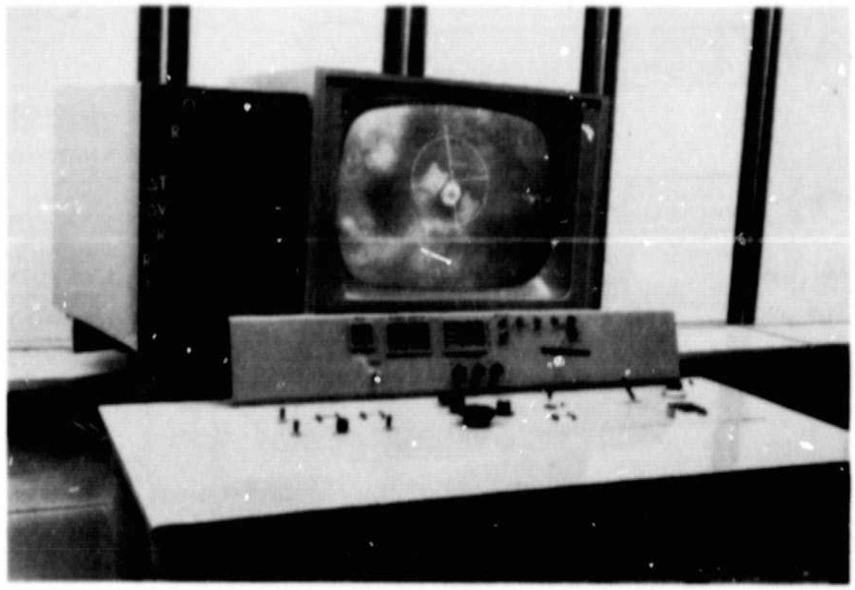

Figure 2-10. Typical Remote Supervisor's Console
(Convair Simulation Study)

Convair's Visual Display Simulator is a manned rendezvous and docking closed loop simulator using commercial video techniques. This simulated ground station display is a composite of separate studio displays including: 1) star background (milky way), 2) target satellite (model of three-axis-stabilized Global Positioning Satellite), and 3) control reticle symbol. The rendezvous and docking kinematics and control simulation are implemented by digital computer software that drives the individual images of the composite display. All degrees of freedom are simulated including simulation of communication delays.

This simulator was instrumental in demonstrating that docking can be accomplished with man providing the equivalent of primary sensor inputs to the Tug-borne control algorithm using only visual information from a television camera. The docking demonstration was accomplished in real time where the operator views the composite motions of the studios as they are being commanded by the computer and in a delayed mode where the operator views single TV frames (taken at 16 second intervals) of the composite motion, makes corrections with the reticle, and observes the results on the next frame. This simulates two operational constraints: the slow scan approach to providing visual information to the operator, and the communication delay in transmitting the visual data.

For both modes, manned, remote docking is accomplished by controlling rotations about the line of sight to the spacecraft while closing at a controlled rate. The selected closure profile consisted of velocity plateaus: from closure back to 25 ft (7.6m), 0.1 ft/sec (0.03 m/s); 25 to 50 ft (7.6 to 15.2m), 0.2 ft/sec (0.062 m/s); 50 to 100 ft (15.2 to 31m), 0.4 ft/sec (0.12 m/s); etc.

Single TV frames were taken on 16-second centers and arrived somewhat randomly 10 to 14 seconds after exposure for the operator's evaluation and measurement via the reticle. The simulation demonstrated that only minor velocity corrections were required in the final 25 ft (7.6m) of closure using a simple least squares linear fit of the most recent eight update measurements from the operator. (Future plans include incorporating a recursive filter as part of a company funded effort.) Docking was scored a success if the actual contact met the misalignment and closuring rate specifications delineated in Paragraph 3.2.1.1.1.4.2 of the Baseline System Requirements document (MSFC68M00039-1).

Analysis and the simulation have shown that television has problems that limit its effectiveness as a terminal rendezvous sensor: 1) the requirement for solar illumination of the spacecraft, 2) the difficulty of obtaining quality range data at distances over 3000 ft (914m), and the necessity of a slow, gradual approach to insure smoothing (filtering) of input data.

Autonomous docking using a scanning LADAR has not yet been demonstrated. Analysis and laboratory testing have shown that LADAR has two problems which limit its effectiveness to perform the docking functions: 1) possible reception of return signals from spacecraft structure that are equal to or greater than the retroreflector returns and 2) pattern discrimination within the field of view at short range necessary to attain alignment lock on the docking port (particularly while rejecting spurious returns).

Direct ascent rendezvous is near optimum in impulse and time and was the rendezvous strategy employed in this study. Autonomous navigation accuracy is on the order of 1.5 n.mi. (2.8 km) (3σ) once the navigation filter has stabilized, and with a priori knowledge of the spacecraft position to within 1 n.mi. (1.85 km) (per the Tug Requirements document, MSFC 68M00039-1) this constitutes an excellent approach for rendezvous with the target satellite. As the Tug gets closer to the navigational rendezvous point, knowledge of the line-of-sight (LOS) vector to the spacecraft degrades. If the LOS vector is to be useful as an update input to reduce the navigational uncertainty, then Spacecraft acquisition using a long range tracking sensor should be established prior to 2500 n.mi. (4625 km). This conditional requirement of measured LOS prior to 2500 n.mi. (4572 km) is based on: 1) providing a reasonable amount of time for smoothing of the LOS measurements, and 2) keeps the LOS angle uncertainty under 0.06 degree (0.001 radian). This range is within the expected capability of TV and LADAR. Reduction of the navigation uncertainty is obtained by actual LOS information being provided to the navigation filter during the period of tracking from 2500 n.mi. (4572 km) to 250 n.mi. (457.2 km). At this time just prior to 250 n.mi. (457.2 km) an accurate range

measurement is needed if further reduction of the navigation uncertainty is to be made and the navigation update is to be complete in time for orientation and insertion burn.

Both the TV and the LADAR were evaluated as long range LOS sensors for spacecraft acquisition and tracking beyond 2500 n.mi. (4572 km). The TV and the LADAR can meet this conditional requirement if the satellite is illuminated by sunlight (the LADAR uses only its detector in this mode). Making the accurate range measurements prior to 250 n.mi. (457.2 km) (a conditional requirement if improvement in the navigation accuracy is desired) can only be performed by the LADAR.

LADAR although presently range limited to 65 n.mi. (1188m) appears to be a desired sensor because of the potential improvements from knowing range to the spacecraft prior to the insertion burn (if 300 n.mi. (556 km) range can be obtained) and because range is required for early relative velocity control for docking after injection. TV is required for visual inspection and docking. It is the most effective system for alignment with the docking port and final docking phases.

Performance of the rendezvous and docking function is not only dependent on the sensors of the rendezvous and docking subsystem, but also on the navigation and guidance capabilities of the Guidance, Navigation, and Control subsystem, the computational support provided by the Data Management subsystem, and the all-attitude communication link to the ground.

Figure 2-11 depicts all of these components although the Tug's baseline rendezvous and docking subsystem consists only of the scanning ladar, the low light level TV, their associated electronics, strobe lights, and the computer memory dedicated to rendezvous and docking software.

The role of each sensor as it relates to the six phases is presented in Table 2-6.

Table 2-6. Sensor Role in Rendezvous and Docking Phases

Function	Scanning Ladar	Slow-Scan LLLTV
Acquisition	Primary	Backup
Tracking	Primary	Backup
Ranging		
Preinjection	Primary	
Postinjection	Primary	Backup
Inspection		Primary
Alignment to Axes		Primary
Closure & Docking		
Initial Operational Capability (IOC)		Primary
Fully Operational	Primary	Backup

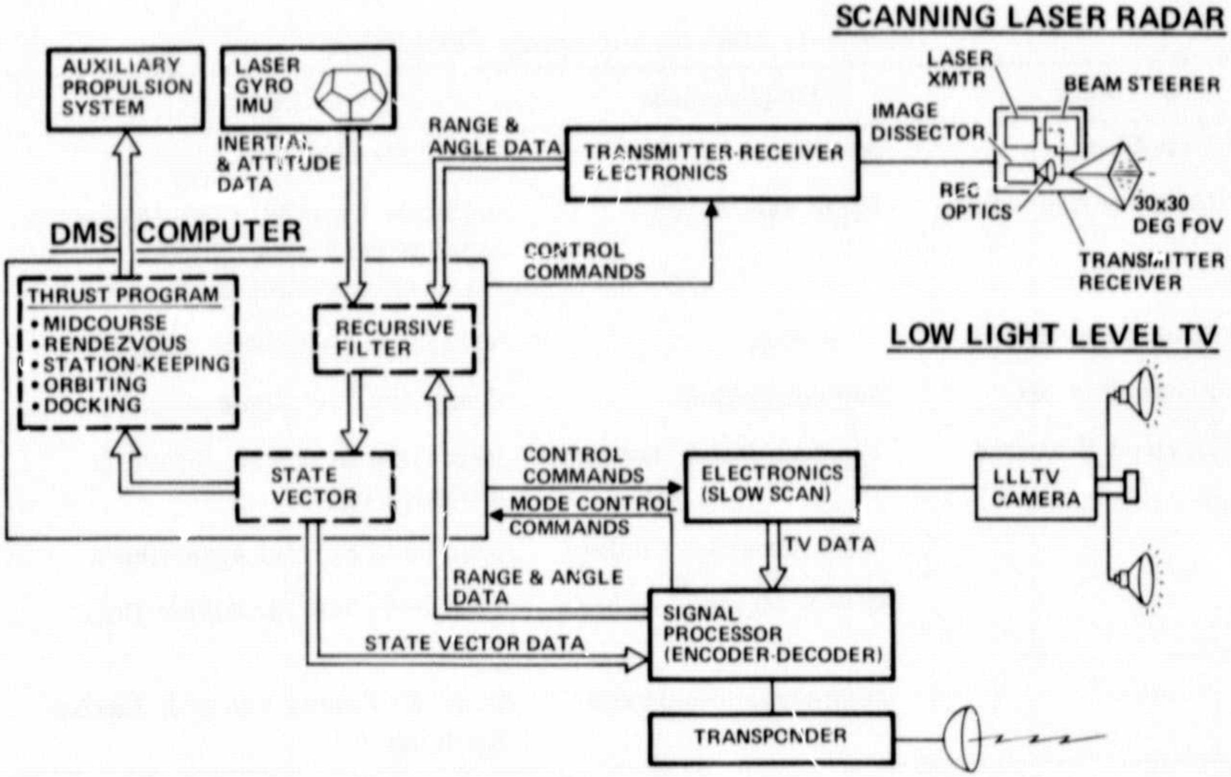

Figure 2-11. Baseline Rendezvous and Docking System

Scanning LADAR sensor technology is well into development. Manned operations seem to be an appropriate application for stereo display technologies, which have been investigated at MSFC. Unknown are the technologies that may be necessary to solve the actual docking function over the spectra of spacecraft that have potential need for retrieval or servicing.

2.3.5 DATA MANAGEMENT SUBSYSTEM. Integration of the complete range of Tug functions is accomplished within the Data Management Subsystem (DMS). The elements of the DMS provide for functional controls, such as automatic tank pressurization; data processing, transmission, and storage; redundancy management; status monitoring; and mission, subsystem, and vehicle sequencing. The DMS accomplishes all this through the use of a central computer and a data bus interfacing with all of the vehicle systems through Digital Interface Units (DIU).

Computer requirements are based on functions that must be performed to integrate the total vehicle system, which are summarized in Table 2-7.

The 32 bit data word is established by the precision required for guidance and navigation computations.

Software estimates for the functions identified represent the minimum memory size the computer should be expected to have. A minimum of 40% growth capability for

Table 2-7. DMS Requirements Established

Item	Requirement	Driver
Data Word	32 bits	GN&C Calculations
Memory Addressing	Up to 48K words	Software Estimate: 30,469 words Utilization Factor: 62% No Auxiliary Memory Required
Processing Speed	>400 Kops	Vehicle & IMU Processing
Instruction Set	360 compatible	Computer Lab Simulations
Desired Features	Floating Point Hardware	Reduction in Coding Effort & Scaling Errors
	Microprogram Control	Speed and Special Algorithms
	Direct Memory Access	Data Bus, IOP & Orbiter Data Interface
	High Order Language	Reduced Coding Effort & Easier Revision

initial estimates is considered adequate. This criterion indicates that a 48K memory is required.

A processing speed greater than 400,000 operations per second is indicated when the processing associated with a dodecahedron IMU is included with the normal system functions.

Compatibility of the computer instruction set with that of a powerful ground based computer is indicated for system simulations in the avionics integration laboratory before flight hardware is available.

Microprogram control and floating point hardware provide the high speed execution of special functions that reduce the effort for coding the software programs. Higher order languages use these functions to improve the accuracy of the programmer's work and to reduce the verification time for functions otherwise created in software.

Direct memory access reduces the burden on the CPU for control of storage for system data and data transfers to the data bus. This data is needed in the central computer memory to accomplish the vehicle functions, but much of it is being generated or used continuously in the other subsystems without relation to the computations being performed by the central computer.

Of the five computers evaluated, including the D232, AP101, HTC, and MOD/LSI110, the SUMC modular computer was preferred. Its modular architecture is particularly

advantageous in overcoming the processing speed limitation of simplex computers. The SUMC employs CMOS/SOS technology, which through lower power dissipation helps reduce temperature in densely packaged units, and has three to five times improvement in speed over MOS devices. Reliability is not a selection driver of redundant computer configurations. Four configurations were evaluated: dual and triple redundant versions of "simplex" computers, and dual and triple redundancy at the module level in the modular computer. All had adequate reliability; the dual modular was lowest in weight.

The baseline DMS configuration is shown in Figure 2-12 and features fault-tolerant SUMC computer, two Computer Interface Units (CIU), eight Digital Interface Units (DIU), and a tape recorder.

The CIU's and DIU's have dual redundant connections to a dual redundant data bus. The data busses are separate entities with cross-strapped connections at the computer and the line replaceable units (LRU) of the subsystem interfaces.

Each LRU can be addressed from either data bus. Since both busses are active, the data format must contain a code to designate which data bus is prime for a particular subsystem LRU.

As part of the redundancy management for error detection and designation of the controlling bus, hardware tests of format and parity will be accomplished in each CIU and DIU. The central computer will participate in the selection of the data bus configuration with hardware and software tests designed to detect failures.

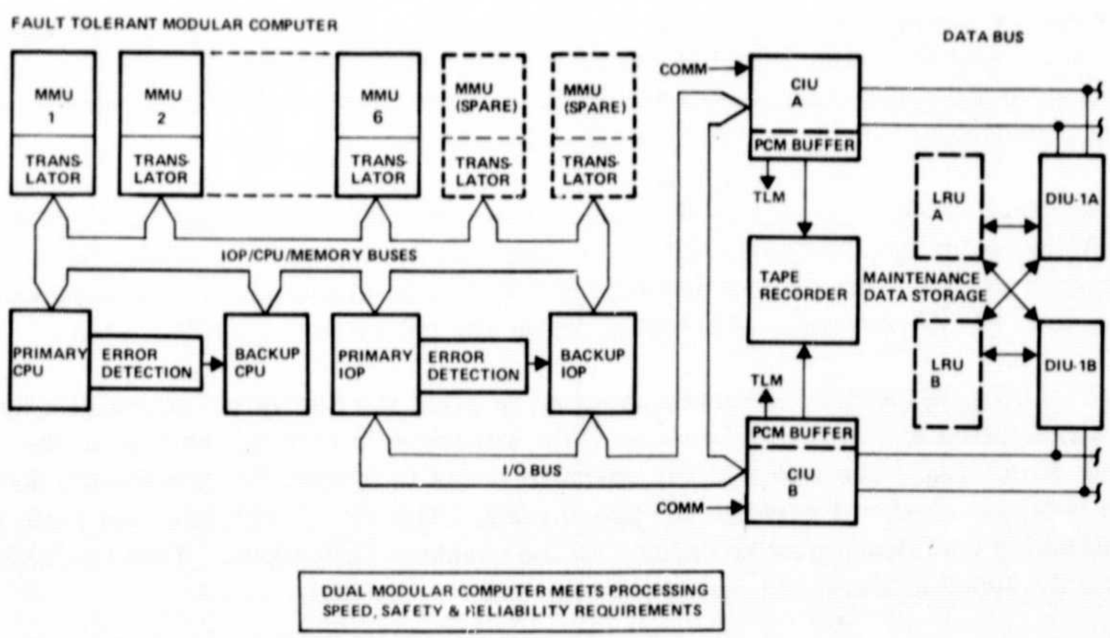

Figure 2-12. Baseline DMS Subsystem

The tape recorder is used to record data for maintenance purposes such as the information related to engine burns. Its capacity of 320M bits will permit recording of the complete first engine burn. This information would then be telemetered to the ground as needed.

The buffer formatter is incorporated into the CIU and is identified as the PCM buffer.

The amount of software involved in a typical Tug mission can be stored in the main memory of the central computer so that a separate storage device typical of virtual memory systems is not required.

Several programming languages were analyzed and rated for effectiveness in accomplishing the coding for Tug missions. These included: Assembly language, Fortran, SPL/J6, JOVIAL, GOAL, and HAL.

The improvement in communication and visibility into coding sequences resulting from high order language programming should reduce the time for software development by 15 to 20%. The reduction of effort in validation and test is a significant part of this improvement.

HAL is the language recommended for Tug software development. Orbiter software will be written in HAL, and language commonality throughout the space program is a great advantage. One of the features of HAL is its capability in arithmetic and matrix manipulation. A significant part of the coding effort for space vehicle guidance and navigation software is involved with matrix mathematics.

Redundancy management, a function of the DMS, must provide the fault coverage required to meet the reliability goal and fault detection/reconfiguration time constraints peculiar to the redundant subsystem. Table 2-8 summarizes the redundancy management approach for all of the avionics subsystems.

The advanced technology of CMOS on a substrate of sapphire is under development. SUMC computer modules using this technology will be delivered in 1976. Redundant computer techniques is another technology being pursued and needs continuing effort to assume 90-95% coverage of potential faults and reliability reconfiguration.

2.3.6 TUG CHECKOUT. Onboard checkout is given the equivalent status of a subsystem description in this report because of its identity as a critical function in the operations of the Tug. The intent of any checkout effort is to establish confidence that the item being checked will perform to expectations. The set of principles set forth in establishing confidence may be defined as the checkout philosophy. These principles define the types of tests, amount of testing, and time to test.

Checkout philosophies cover the spectrum from no testing to extensive testing. Six different philosophies were evaluated with respect to confidence, nonrecurring and

Table 2-8. Redundancy Management

SUBSYSTEM	LEVEL REDUNDANCY	TYPE OF REDUNDANCY	REDUNDANCY MANAGEMENT APPROACH
DATA MANAGEMENT			
COMPUTER	DUAL (MODULAR)	PRIMARY + STANDBY	CPU/MEMORY HARDWARE CHECK AND SWITCH
DATA BUS	DUAL	INDEPENDENT CHANNELS	CIU CHANNEL CHECK WITH IOP SWITCH DIU CROSSTRAPPED TO LRUS
GN&C			
IMU	DODECAHEDRON	MULTIPLE SENSORS	DMS SOFTWARE PROVIDES: SENSOR DATA COMPARISON SELECTS SENSOR SET FOR COMPUTATION DETECTS SENSOR FAILURE & RESELECTS SENSOR SET
ILT (POS, VEL UPDATE)	FAULT TOLERANT	MULTIPLE CHANNELS	
ATTITUDE UPDATE	DUAL	ONE + SPARE	POWER UP/DOWN
FLT CONTROL	TRIPLE	MAJORITY VOTING	SELF-CORRECTING
RENDEZVOUS/DOCKING			
SENSORS	DUAL	PRIMARY + BACKUP	POWER UP/DOWN
COMMUNICATION			
PHASED ARRAY	FAULT TOLERANT	MULTIPLE-ELEMENT ANTENNA	GRADUAL DEGRADATION
SIGNAL PROCESSING	DUAL	INDEPENDENT CHANNELS	DMS SOFTWARE CHECK/ SWITCHING
ELECTRICAL POWER			
FUEL CELL	DUAL	ONE + SPARE	SELF-DETECTION & CORRECTION

recurring support. They were: 1) hand-off (use to failure), 2) hard time remove and replace (replace every Δ time, event or cycle), 3) hard time test (test every Δ time), 4) test and retest (repeated preflight tests), 5) condition monitored maintenance (CMM), (replace only on trend data), and 6) CMM with preflight test (CMM_{PF}) (active preflight test augmented with flight data). CMM_{PF} provides the maximum confidence for a low program cost. The Tug checkout tasks were established based on this philosophy.

Six categories of tests were defined, which encompass all of the checkout activities in the Tug under the CMM_{PF} philosophy. These checkout categories are: safety monitoring, status checking, initialization (load and verify flight programs and target vectors), calibration, functional test, and maintenance support.

All of the component level units were evaluated to determine the applicability of each test type to each of the components during each flight and ground operational phase. The test requirements matrix in Table 2-9 summarizes the total number of components undergoing the different tests during the 10 mission phases identified. This matrix represents the CMM_{PF} philosophy, which guided the judgement as to what units get tested, when, and by what test type. The exceptions to this philosophy represent the functional test of the computer and the computer interface units during shuttle ascent, and the optical sensors and rf system on-orbit where the operational condition is best for their functional checkout. The matrix distribution leads to a sensible allocation of where the responsibility for performing the test should be placed based on the following criteria: recurring test demands (status test, maintenance support), phase-peculiar testing (safety monitoring, functional tests, calibration, initialization), and the requirement for high support software storage used in few mission phases (functional test).

Table 2-9. Test Requirements Summary Matrix

Mission Phases	No. of Components Undergoing Test					
	Safety	Status	Calib.	Funct. Test	Initial.	Maint. Support
Prelaunch	2	8	10	25	5	0
Shuttle Ascent	8	22	1	5	14	2
On Orbit	9	30	1	12	12	2
Tug Deploy	9	28	0	1	2	8
Tug Ascent	0	20	0	0	0	6
Payload Deploy	0	24	0	0	3	7
Tug Descent	8	24	0	0	1	7
Orbiter Capture	9	26	0	0	0	0
Shuttle Descent	2	12	0	0	0	0
Gnd Ops	1	4	10	35	20	11

The allocation of the test responsibilities is shown in Table 2-10. Those tests under "Tug Allocation" will be implemented with software residing in the central computer. The prime elements of this software are status verification and inflight maintenance support data acquisition. The other tests will also be implemented with test support software residing in 1) the Launch Processing System at KSC for the majority of functional tests, calibration and the software associated with postflight maintenance data processing, and 2) the Orbiter for evaluation of the safety monitoring data. The test support software memory storage requirements are also shown in Table 2-10.

Figure 2-13 is an overall view of the Tug onboard checkout system. Checkout has its major impact on the Tug avionics system in the area of computer memory storage for software instruction programs and data. The capacity of the Data Management Subsystem was sized with the checkout tasks considered. The instrumentation subsystem (right-hand side of the figure) depicts the following response data sources:

Line Replaceable Unit (LRU) is the component level in the Avionics System. The LRUs may contain varying degrees of built-in test equipment (BITE), from no BITE where many test parameter response data are provided to evaluate the health of the unit, to total BITE within the unit where one parameter indicates the go/no-go status of the unit. Special LRU instrumentation measurements are conditioned and multiplexed by means of the signal conditioner unit. Additional instrumentation is provided to acquire data relating to unit performance in flight in support of the ground maintenance function. The central computer has the capability of formatting any or all of the acquired data for transmission to the ground via telemetry. The maintenance data can also be stored in the tape recorder for later transmission or post-flight read-out.

The prime test activities of the onboard checkout system are safety monitoring, status verification, and maintenance support data acquisition.

Table 2-10. Checkout Allocation

Ground Allocation	Orbiter Allocation	Tug Allocation
Functional Test Calibration Maintenance Processing	Safety (monitor) (No decom or display formatting included)	Safety (reaction sequence) Status Initialization Partial Functional Critical control loops Critical functions and components Maintenance Data Acquisition
88K Words Total	1.5K Words Total	8.9K Words Total

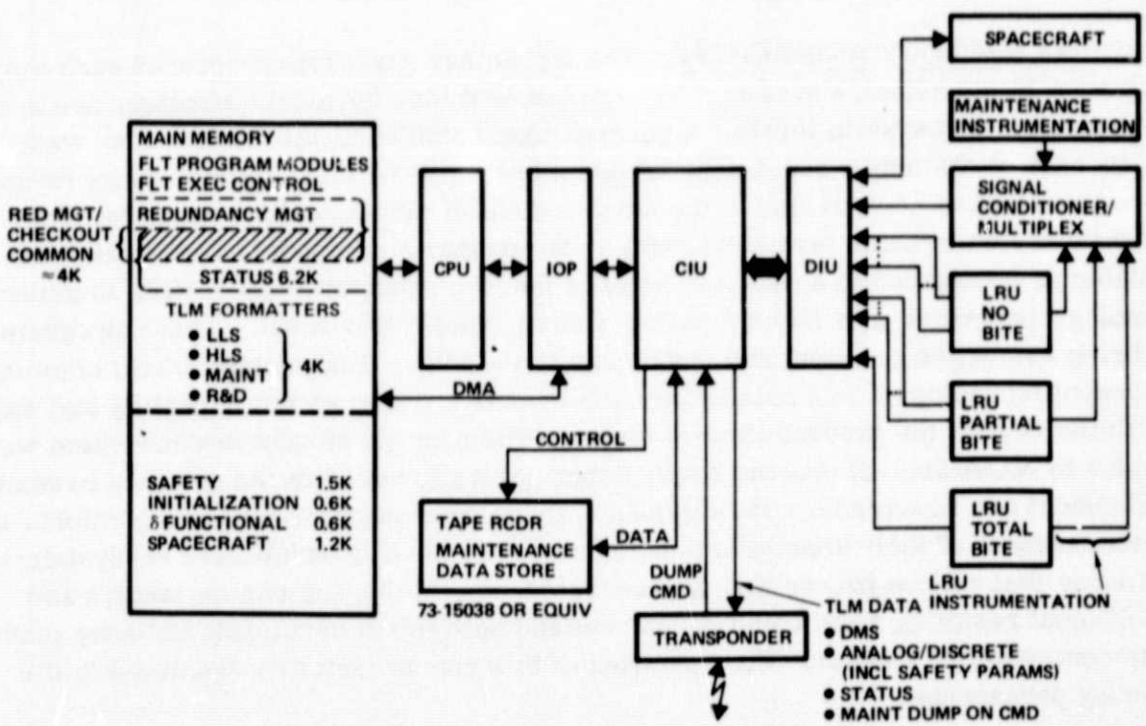

Figure 2-13. Tug Checkout System Block Diagram

2.4 PROGRAMMATICS AND COSTS

The Tug avionics system definition includes selected advanced technology components and concepts. With Tug avionics development planned to start in late 1978, an assessment was made of the current status of those technologies for the purpose of defining the technology base most likely to exist in 1978 in order to estimate a low risk, low cost, orderly development of the Tug avionics. The 1978 projection was based on accomplishments to date and on current and probable future funding. On-going technology programs in government and industry were identified. This technology base became the basis for determining the Phase C/D design and development tasks, which in turn led to the cost estimate for avionics development. Risk was an important influence in the cost estimating methodology and was accounted for through the use of uncertainty factors developed by comparing the probable 1978 technology status against the Phase C/D tasks to be accomplished. Two estimates were made: one representing minimum progress of the technologies, thereby increasing the avionics development efforts and the cost uncertainty having to prove out concepts during development; the other representing a realistic advancement in those technologies, and therefore increased confidence in the estimated development efforts and a lower cost uncertainty. The recommended plan for Tug avionics development was then defined.

2.4.1 TECHNOLOGY ASSESSMENT. The technology assessment covered each major component in the avionics system. The assessment also covered technology needs at the subsystem and system levels. A general conclusion from this assessment was: 1) that in each of the major component areas, there is some on-going technology program in progress that is contributing to the advancement of the technology needs for Tug, 2) that deficiencies in these programs exist as to whether a component application will be available or configured in a way that benefits the Tug program, and 3) that, in general, technology programs are lacking at the system/subsystem level. These programs can bring innovative concepts and techniques to the major Tug problem area: combining component technologies into unique functional entities that push the capability and capacity limits beyond the present state of the art. The benefits of subsystem/system technologies to NASA are: 1) that the NASA Laboratories involved in the avionics technology development can receive important guidance from the subsystem technology efforts in the development of their appropriate components, 2) the Tug would have subsystem level techniques that will be proven and demonstrated, and 3) the Tug can maintain a low DDT&E cost resulting from these component and subsystem developments being part of the continuing SRT effort. The specifics of this assessment are discussed in the following paragraphs.

DMS Components. Modules of the SUMC digital computer are being developed in an on-going program that includes configuration verification testing – scheduled at MSFC in 1976/77. This testing is for a simplex configuration and is for application of the SUMC to the Spacelab program. Redundant hardware investigations are lacking if this program is to support the Tug program.

Fault tolerant memories are in the breadboard development phase. This is a critical technology for Tug. Spare memory planes as well as spare memory modules are superior to providing complete redundant memories.

The data bus uses current technology in development for the Shuttle, B-1, and other programs. DIU's and the CIU utilizing LSI technology and power reducing techniques need early concept work.

DMS Subsystem Technologies. Computer redundancy is the limiting technology when considering the Tug program requirements. The compatible integration of redundant memories, CPU's, IOP's, and data bus components relies on subsystem/system level technology work investigating such techniques as fault and error detection and handling software traffic and switchover approaches involving automatic cross-strapping. The investigation of redundancy management techniques both internal to a modular computer and external out to the LRU's is key to the development of the whole data management process and has no currently funded effort underway.

GN&C Components. Experimental hardware of the laser gyro IMU in a simplex configuration is currently being tested in an on-going program at MSFC. A dodecahedron configuration is being designed. Star tracker/sun sensors are essentially off-the-shelf units but will need adaptability and software for the Tug missions. For the interferometric landmark tracker — the techniques are understood and hardware components are in design; however, adaptability to the Tug needs to be demonstrated.

GN&C Subsystem. As observed from the GN&C baseline configuration diagram, the major effort in this subsystem is software. Several technologies need investigation with unique applications to Tug requirements, such as recursive filtering for ILT, star tracker, sun sensor information as it applies to navigation update capability, fault detection, isolation and reconfiguration dodecahedron sensors, and unique methods of combining sensor inputs for optimum accuracy capability. Yet these are not being pursued.

Rendezvous and Docking Components. Scanning laser (LADAR) laboratory units are being developed and need on-going effort. The TV camera is off-the-shelf hardware. This study has demonstrated the feasibility of manned remote rendezvous and docking. Stereo TV-type displays have future applicability to this function. Work is going on now at MSFC on stereo display techniques.

Rendezvous and Docking Subsystem. In this subsystem also, recursive filtering will play a major role in the accuracy and adequacy of the sensor or combination of sensors employed. Control algorithm investigations for the docking phases is a driving technology. Techniques of improving position uncertainty with respect to the target for rendezvous using long-range line-of-sight information only can be of great benefit as a potential update technique. These are important system-level technologies having no current effort.

Communications Components. Phased array hardware is being developed. The "transmit only" requirement (newly defined by this study) should be factored into that program. Techniques for optimum signal processing to obtain network compatibility are being pursued in the industry.

Communications Subsystem. Dual redundancy in this subsystem requires redundancy management techniques to handle automatic reconfiguration. Cross-strapping techniques were defined using Shuttle technology. Confidence levels will generally be high in the technique employed in this subsystem at time of Phase C/D requiring a lower technology effort.

Electrical Power Components. The power plant element of the Shuttle's electrical power system is an on-going program as well as the adaptation of that high pressure supercritical storage fuel cell to the Tug. The 1976-78 technology fuel cell, called the lightweight fuel cell, has also been in development, and cells of this technology have been built and tested. This latter technology approach to the power plant has been defined as the baseline configuration for Tug. Support of its development is crucial. Parallel work should continue using the Shuttle-type power plant to investigate low pressure operation, helium contamination solutions, redundancy implementations, etc., as a low risk backup to the lightweight technology.

Electrical Power Subsystem. The reliability of this subsystem will come from the redundancy techniques employed in the many other elements of this subsystem. Thermodynamic technologies are key to the efficient use of waste heat versus heating requirements in this system. Redundancy management techniques are also vital to the automatic reconfiguration approach to maintain a fail operational system. No effort is being pursued in this area. Power plant development is only one element in this complex subsystem.

Instrumentation Components. Maintenance support is a driver of special instrumentation requirements particularly oriented toward mechanical systems where rotating equipment is involved. Sensor technologies associated with acoustical emission are being studied and developed. Potential for passive detector development is seen for chemical, temperature, and vibration sensitive paints, strips or fusing compounds used in limit detecting, and bi-state nonreverting applications with no electrical interface. Magnetic accumulator plugs in lubricant reservoirs detect wear. With reusability provided by the Tug, post-mission assessment of component condition is an important function.

Instrumentation Subsystem. Technologies at this level include investigating techniques for the verification of redundant paths and the assessment of mechanical system readiness. The unique applications of microprocessors and variable (programmable) gain amplifiers require technology-level effort prior to development.

These subsystem technologies have applicability to spacecraft and other upper stage programs as well as the specific benefits to the Tug program as outlined. Without timely pursuit of these technologies, the integration of the component technologies becomes a Phase C/D development task with attendant increases in risk and uncertainty in accomplishing the development task within the estimated cost. Pursuit of component technology alone does not guarantee a compatible subsystem development. The subsystem technologies need to be funded directly from SRT funds, or these technology activities need to be carried under major NASA program funds.

2.4.2 AVIONICS COST SUMMARY. A "detailed estimate /build-up" approach was used to determine costs. For each major subsystem, a work sheet was prepared as follows. Engineering design and development data (such as power, weight, size) for each component of the subsystem was listed. Basic buy shipset cost was obtained from vendor data (documented vendor costs were obtained on all major components) and/or analogs from existing/similar components, particularly recent Centaur information. Costs were increased by 10 to 90% to allow for the effects of uncertainties on cost. Experience on past programs shows that this is the expected range of cost uncertainty. The absolute value depends strongly on the state of the art at Phase C/D go-ahead plus the interdependence between subsystems as they are being developed concurrently. The value of uncertainty cost applied to each component or subsystem was determined from the technology assessment described in Section 2.4.1. Convair Engineering Design costs were estimated for each subsystem, based on comparison with similar tasks for which actual cost were available. Total subsystem costs were generated by adding buy costs and Convair design costs with allowances for other Convair costs (such as design analysis, tooling, and reliability) determined from our historical experience data. The resulting costs were collected into the two categories: Engineering Design and Development, and Total DDT&E.

A summary of Tug avionics development costs is shown in Table 2-11. These costs are shown for the two conditions of technology advancements. The left column represents a minimum of technology work prior to 1978. This will result in a predicted total avionics system DDT&E cost of $94 million. The associated uncertainty factors are shown in the left numerical column of the table. The factors range from 20 to 70%, primarily because advanced state of the art components are being integrated into subsystem/ systems and these tasks are taking place concurrently.

To reduce the uncertainty factors and hence the development costs, activities can be pursued during 1975 through 1978 aimed at reducing the interdependence between subsystems and at improving the definition of components/subsystems/systems before producing test/qualification/flight hardware during the Phase C/D program. The avionics costs can be reduced to $75 million (20% reduction) if these technology activities are accomplished during 1975-78. These activities encompass supporting research and technology simulation-demonstration and other pre-phase C/D activities that decrease subsystem interdependence and increase subsystem confidence. These 1975-78

Table 2-11. Cost Summary (Million dollars)

	MINIMUM TECHNOLOGY FUNDING 1975-78		RECOMMENDED TECHNOLOGY FUNDING 1975-78	
	COST UNCERTAINTY FACTOR	PHASE C-D COSTS	COST UNCERTAINTY FACTOR	PHASE C-D COSTS
DATA MANAGEMENT				
DIGITAL COMPUTER	70	9.0	30	7.0
DIGITAL DATA BUS	30	2.4	10	2.2
TAPE RECORDER	30	0.2	10	0.2
GUIDANCE, NAV & CONTROL				
IMU	70	9.8	30	7.6
GUIDNACE UPDATE	50	4.7	20	3.9
RATE GYROS	70	6.3	20	5.2
CONTROL ELECTRONICS	40	3.7	10	2.9
RENDEZVOUS & DOCKING				
LASER RADAR	70	12.6	30	10.1
TV CAMERA & ELECT	20	1.7	10	1.6
ELECTRICAL POWER				
POWER SOURCE	60	7.6	20	5.7
THERMO/PRODUCT WATER	50	1.3	20	1.1
POWER DISTRIBUTION	40	2.5	10	2.1
COMMUNICATIONS	60	11.2	20	9.2
INSTRUMENTATION				
TRANSDUCERS + WIRING	50	5.2	20	4.2
SIGNAL CONDITIONERS	40	3.7	10	3.0
SYSTEM INTEGRATION		6.2		4.6
SOFTWARE	140	5.8	70	4.7
TOTAL		94.0		75.3

activities comprise the first three years of the recommended avionics development program discussed in the next section.

2.4.3 <u>AVIONICS SYSTEM DEVELOPMENT PLAN.</u> The recommended development plan incorporates 1975-78 activities that will result in a high confidence/low risk/low cost Phase C/D program. The plan is shown in Figure 2-14.

Because data management/software/system integration is the focal point for the interdependence of all other avionics subsystems, a key milestone in the plan is the operational date of a Tug Avionics Integration Laboratory (TAIL). A date of October 1979 coincides with the Tug Preliminary Design Review when typical activities are: review requirements, firm system specifications, review performance and design requirements, identify critical components, complete major design layouts and schematics, and initiate procurement of long-lead items. A key accomplishment of the 1975-79 activities should be to demonstrate the feasibility of the integrated avionics system.

This appears to be an optimum schedule time for accomplishing a demonstration of the functional operation of the Tug avionics system. Should it be later, specifications to procure hardware would be released without the benefit of the feedback from such a demonstration. Should it be earlier, interference with the peak funding years of the Shuttle would be increased.

Backing up from this date would require approximately 1-1/2 years of integrating the DMS with the other subsystems, validating the hardware/software interfaces, demonstrating that the proposed redundancy management schemes are reasonable. Hardware

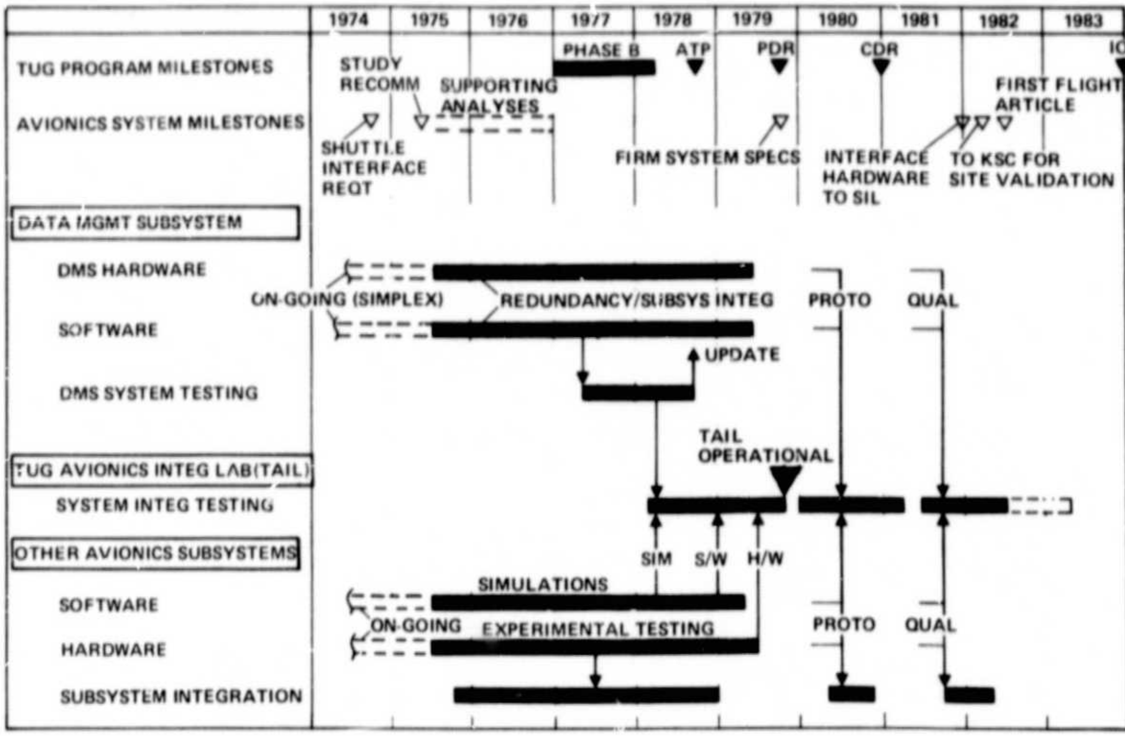

Figure 2-14. **Avionics System Development Plan**

for the data management system and software must be developed in a timely way to support the integration activity and this is shown starting in 1975. The on-going simplex SUMC computer program needs to be extended to the redundancy configuration needs of the Tug program and subsystem testing completed by early 1978. The DMS subsystem can then be extended into integration activities during 1978-79.

To support the integration activities, the functional interfaces of the other subsystems need to be analyzed and defined for software requirements to be established. Simulation of interfaces can follow by software/hardware substitution as it becomes available from these parallel activities. Integration at the subsystem level will be developing during 1976-78, and an integration laboratory will be available for each major subsystem of electrical power, guidance/navigation, rendezvous/docking, communications, and data management. These subsystem integration laboratories and the avionics integration laboratory can all be used during the Phase C/D program to verify prototype and flight hardware. Supporting plans for each subsystem are detailed in Volume V.

SECTION 3

SUPPORTING RESEARCH AND TECHNOLOGY RECOMMENDATIONS

Development costs of Tug avionics will depend on the scope of SRT activities applied to proofing concepts and techniques during these years ahead of Phase C/D start. This section presents the planning and recommendations for specific SRT efforts that will lead to a low-cost, low-risk program for avionics development. The plan recommends subsystem SRT work complementing and enhancing the component technology activities, directs the SRT toward the Tug program (but with general applicability to other NASA programs), and establishes schedules and expected goals to be reached through SRT. The specific SRT tasks fall within five general categories of activities that represent the steps through which SRT projects should progress before specifications are released for hardware and software procurement. (See Figure 3-1.)

3.1 RECOMMENDED TECHNOLOGY EFFORTS 1975-78

Table 3-1 shows the SRT activities that should be pursued. Component and subsystem technology activities are listed for each of the major subsystems. There are on-going technology programs for most of the major components of the Tug avionics system; the major exception is the lightweight fuel cell, which needs to be started. In contrast, there are practically no on-going technology programs at the subsystem/system level. A major recommendation of this study is that SRT activities at the subsystem/system level should be initiated and should proceed in parallel with the component level activities. Both types of activities are needed if the low development cost of $75 million is to be achieved.

An important feature of the SRT plan is that it should progress year by year until the characteristics shown in Figure 3-1 are achieved. Figure 3-2 shows the major milestones of the SRT activities. These milestones are the goals for measuring progress, establishing continuity for each SRT sub task, and establishing annual priorities and allocating SRT funds.

3.2 RECOMMENDED SRT FOR FY 76

Based on the current technology status of each of the components/subsystems in the SRT program, Table 3-2 shows the SRT activities that should be funded in FY 76. These are the technologies of Tug avionics that have the potential of becoming schedule or cost drivers unless SRT activities are pursued.

As shown in Table 3-2, most of the component level activities are on-going. Technology for the lightweight fuel cell is the main new start. At the system level, practically all of the recommendations are new. The major recommendation of this study is that system level SRT activities should be pursued in parallel with the on-going component level activities.

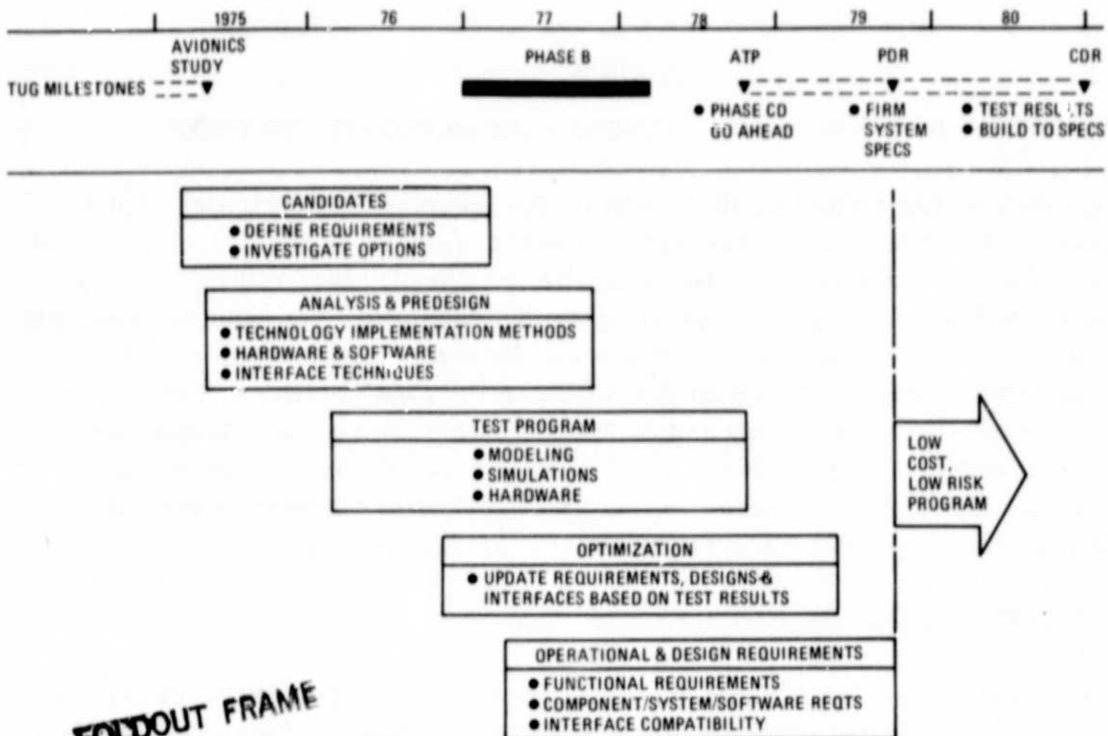

Figure 3-1. Categories of SRT Activities

Table 3-1. Recommended Technology Efforts 1975-78

	COMPONENT	SUBSYSTEM/SYSTEM
DATA MANAGEMENT	• FAULT-TOLERANT MEMORY TECHNIQUES & TESTING • REDUNDANT RECONFIGURATION TECHNIQUES • DIUs & CIUS USING LSI/POWER REDUCING TECHNIQUES	• REDUNDANCY MANAGEMENT TECHNIQUES: FAULT DETECTION & ERROR CORRECTION APPROACHES SOFTWARE TRAFFIC MODELING AUTOMATIC CROSS-STRAPPING TECHNIQUES
GUIDANCE NAV & CONTROL	• DODECAHEDRON LASER GYRO IMU TESTING • ADAPTATION OF UPDATE SENSORS TO TUG REQUIREMENTS	• MULTISENSOR FAULT DETECTION/RECONFIGURATION TECHNIQUES • UPDATE SENSOR COMBINATIONS MODELING • MULTISENSOR INPUT FILTER MODELS
COMMUNICATION	• OPTIMIZE SIGNAL PROCESSING & MODULATION TECHNIQUES • ADAPT PHASED ARRAYS TO "TRANSMIT ONLY" REQUIREMENT	• REDUNDANCY MANAGEMENT TECHNIQUES FOR AUTOMATIC RECONFIGURATION • ADAPT SHUTTLE CROSS-STRAPPING TECHNIQUES TO TUG REQUIREMENTS
ELECTRICAL POWER	• ESTABLISH LIGHTWEIGHT FUEL CELL TECHNOLOGY: DESIGN & BUILD UNIT CONFIGURATION PERFORMANCE TESTING USING MAIN PROPELLANTS • MODIFY SHUTTLE FUEL CELL (BACKUP) LOW-PRESSURE TESTING He CONTAMINATION TESTING	• THERMAL INTEGRATION TECHNIQUES • REDUNDANCY MANAGEMENT/AUTOMATIC RECONFIGURATION TECHNIQUES TO ACHIEVE A FAIL-OPERATIONAL CONFIGURATION
RENDEZVOUS & DOCKING	• HIGHER POWER LASERS • CLOSE-IN SENSOR FOR DOCKING • SOLID-STATE IMAGE CAMERAS • RELIABILITY IMPROVEMENTS	• STUDY/MATH MODELING/SIMULATIONS FOR: • IMPACT OF SERVICING FUNCTION ON RENDEZVOUS & DOCKING • AUTONOMOUS CONTROL ALGORITHM SIMULATIONS FOR DOCKING • OPTIMUM COMBINATION OF SENSORS • LOS TECHNIQUES FOR IMPROVING POSITION ACCURACY (INTERACTION WITH GN&C SYSTEM)
INSTRUMENTATION	• TRANSDUCER DEVELOPMENT • PASSIVE DETECTORS	• REDUNDANCY VERIFICATION TECHNIQUES • APPLICATION OF MICROPROCESSOR TECHNIQUES

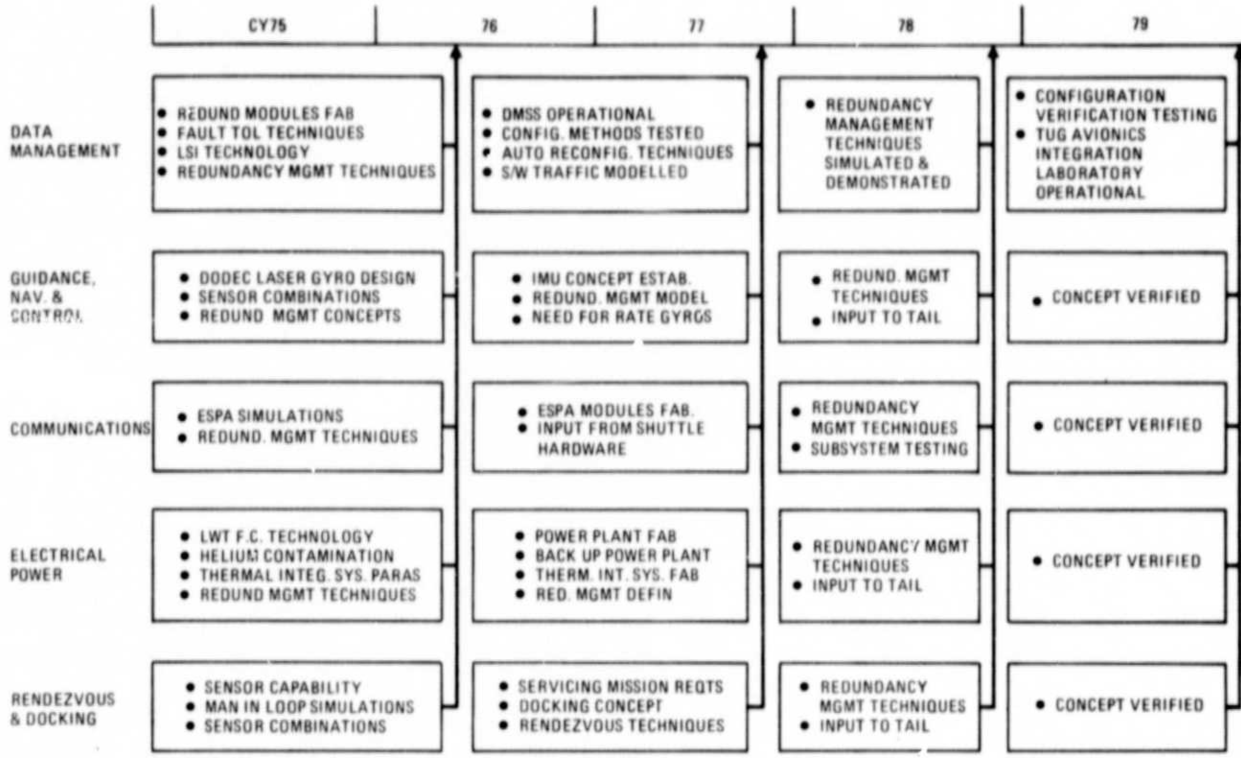

Figure 3-2. SRT Milestones

Table 3-2. Recommended SRT for FY 76

	COMPONENT LEVEL SRT	SYSTEM LEVEL SRT
DATA MANAGEMENT	LSI TECHNOLOGY (0) FAULT TOLERANT MEMORY (0) REDUNDANT CONFIGIRUATIONS (N)	REDUNDANCY MANAGEMENT TECHNIQUES (N)
GUIDANCE, NAV & CONTROL	DODECAHEDRON LASER GYRO (0)	REDUNDANCY MANAGEMENT (N) OPTIMUM SENSOR COMBINATIONS (N)
ELECTRICAL POWER	LWT FUEL CELL TECHNOLOGY (N) LOW PRESSURE MODIFIED ORBITER FUEL CELL (M)	SYSTEM DESIGN/THERMAL INTEGRATION (N) REDUNDANCY MANAGEMENT TECHNIQUES (N)
RENDEZVOUS & DOCKING	SENSOR CAPABILITY (0)	MAN-IN-LOOP SIMULATIONS (0) OPTIMUM COMBINATION OF SENSORS (N)
COMMUNICATION	PHASED ARRAY (M)	REDUNDANCY MANAGEMENT TECHNIQUES (N)

(N) = NEW (M) = MODIFIED (0) = ON GOING